The Report Committee for Edward Michael Buono

Certifies that this is the approved version of the following report:

Aquaponics as a Senior Capstone Design Project

APPROVED BY

SUPERVISING COMMITTEE:

Supervisor: ______________________________

Richard Crawford

____

Anthony Petrosino

Aquaponics as a Senior Capstone Design Project

by

Edward Michael Buono, B.A.

Report

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Arts

The University of Texas at Austin

August, 2014

Dedication

This report is dedicated to my son, Brady, my wife, Shelly, and everyone else in my family.

Acknowledgements

I would like to acknowledge all of the staff at Uteach*Engineering* for their help and dedication to this program. In particular, Dr. Rich Crawford, for all of the invaluable help he gave me as an adviser through this project.

I would also like to thank the people who helped me think about this design, in particular my father, who I could not have done this without. Also, a huge thanks to Jerry Moldenhauer, and Scott Mitzel for helping me with the construction of the system. Thank you, Chris Buono, for never giving up on me and for planting the seed that sparked the interest to do this.

Finally, thanks to the best cohort one could ask for. You made this experience worthwhile. Specifically, Spencer Martin, who was never afraid to ask the tough questions while also providing the humor we all needed to make it through.

Abstract

Aquaponics as a Senior Capstone Design Project

Edward Michael Buono, M.A.

The University of Texas at Austin, 2014

Supervisor: Richard Crawford

Abstract

This report is an exploration of using aquaponics as a means to create a senior capstone design project in a K-12 setting. The relevant world issues related to food production and resource scarcity, as well as the need to integrate STEM subjects in a more interconnected way, justify this project as robust in a high school setting. The report gives details on the design and construction of a backyard aquaponic system, along with a discussion of the performance of this actual system. This experience informs the design of a curriculum for a high school engineering classroom which is presented in outline form.

Keywords: Aquaponics, Engineering Education, Integration, Post-Modernism

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

According to the Population Reference Bureau, the population of Earth is slated to rise to over 9 billion people by the year 2050. ("2013 World Population Data Sheet") The growth will be most prevalent in less developed countries, as the more developed countries only see slight growth over the same time period. What is particularly disturbing about this metric is that human consumption is currently greater than the regenerative capacity of the planet. "Humanity's demand on the plant's living resources, its Ecological Footprint, now exceeds the planet's regenerative capacity." (2008 Living Planet Report 2) Of course, this is made possible by fossil fuels, as the ancient stored sunlight of the past fuels the economies of the present. As the world population continues to increase, so will the demand for food and water.

Current food production in the United States is dominated by large agribusiness. Modern agriculture utilizes heavy machinery, irrigation, fertilizers, and pesticides in order to mass produce the amount of food required to support our population. Petrochemicals abound in the process of creating our food and are present in our fertilizers, pesticides, herbicides, and fungicides (Bernstein 14). Oil is a not a renewable resource. Despite the fact that we continue to find new ways of extracting oil that are more efficient, such as hydraulic fracturing, there is no debate that oil is a limited resource that will eventually run out. As the affluence level of emerging countries increases, particularly in Asia, this demand for oil will also continue to rise. "Because oil is so intricately woven into every aspect of our current food-production system, increasing oil prices will affect the price of food, perhaps dramatically" (Bernstein 15).

1.1 The Nitrogen Cycle and Aquaponics

The problem of relying on petroleum products as a means to feed the world is truly quite pervasive. In fact, the National Academy of Engineering lists managing the nitrogen cycle as one of the grand challenges of our time, stating that "Human production of additional nitrogen nutrients, however, has now disrupted the natural nitrogen cycle, with fertilizer accounting for more than half of the annual amount of nitrogen fixation attributed to human activity." (Manage the nitrogen cycle - Engineering Challenges) This fixed nitrogen, until modern times, was only available and created through microorganisms and lightning strikes. (Manage the nitrogen cycle - Engineering Challenges) That was until Fritz Haber developed the process of fixing nitrogen, by combining hydrogen and nitrogen with an iron catalyst under high temperatures and pressures, into ammonia. By 1913, Fritz Haber and Carl Bosch made this process viable on a large scale, which is the basis of almost all of the fertilizers in use today. (Modak 69) Although this process is responsible for feeding most of the world's population through the use of fertilizers, there are unintended consequences. One of these includes the addition of nitrous oxide, a greenhouse gas 200 times more potent than carbon dioxide, to the atmosphere. Also, the fertilizers and other additives that are added to crops are flushed into the water supply via runoff, and thereby pollute our drinking water, waterways, and coastal deltas. "Among the consequences are worsening of the greenhouse effect, reducing the protective ozone layer, adding to smog, contributing to acid rain, and contaminating drinking water." (Manage the nitrogen cycle - Engineering Challenges)

Texas is a state where water is scarce. Texas generally moves through cycles of drought, ranging from exceptionally dry to extreme drought. More recently, in 2011 nearly the entire state of Texas was under an "exceptional drought" which is the worst categorization. (Dried Out: Confronting The Texas Drought) It was the worst drought in Texas's recorded history. According to NPR, "the current drought began in October 2010" and has caused thousands of square miles to be burnt by wildfires, and billions of dollars to be lost in agriculture. (Dried Out: Confronting The Texas Drought) Modern agriculture not only relies on access to water for crops, but also pollutes water via runoff. Texas is not a state that can take water for granted, and has put together several plans for the future in sustaining its water supply for its growing population.

A potential solution to both the nitrogen cycle as well as the use of water for agriculture is aquaponics. Aquaponics is the fusion of aquaculture, raising fish, and hydroponics, growing vegetables without soil. The process of aquaponics is quite simple. Fish excrete ammonia as waste, nitrosomonas bacteria convert the ammonia to nitrite, then nitrospira bacteria convert that to nitrate. The plants filter the nitrate out of the water, and the water is returned to the fish tank. This closed loop system uses one-tenth of the water than conventional gardening, and does not need any nitrogen based fertilizers to be added as an input to the system. (Bernstein 28) Fish food and trace elements need to be added for plants that require a more robust nutrient load.

1.2 Project-Based Learning

Recently, the field of education has taken an interest in trying to change old ways of teaching subjects. One of the biggest pushes has been by educators, the federal government, and industry to advance Science Technology Engineering and Mathematics (STEM) education by sparking interest in minds of young people. There is a fear that the United States will lose its “technological edge in research and development in a wide variety of technological fields.” (Kubel) As students track through their education, they either lose interest or gain interest in science or mathematics courses. Eventually, they choose a major for post-secondary education, and either pursue a degree in a STEM field or not. The result of this process is commonly called the “STEM pipeline” and the goal is to decrease the amount of students who are “leaking” out of it. “While the pipeline for STEM professionals leaks in many places, it is clear that the end of high school and beginning of college is a critical juncture.” (Singer 2)

An integral way students are being engaged in STEM throughout school is by introducing them to real life, relevant problems that engage their interest before they reach post-secondary studies. The method employed, project based learning (PBL), is designed to grab a student’s interest through rigorous and relevant problems that are not necessarily focused on a single academic subject. Integration or combining more than one subject in a specific project, is a goal advocated in (National Academy of

Engineering). The idea of integration is combining multiple subjects and focusing on the big ideas that interconnect them. *The goal of this research is to ultimately design a unit that can be applied in a high school setting, that integrates multiple subjects together, either in the maintenance of, or design of, an aquaponics system*. Because of the relevance to issues that students' will be able to grasp, particularly in a high school setting, and how this project integrates a focused perspective that starts on a global scale then funnels down to a local situation, it will prove fruitful for high school students.

The remainder of this report is organized by first looking at relevant literature regarding engineering education. Following the literature review will be the design considerations that were taken into account while learning about aquaponics. After that, the construction process I went through is detailed followed by the cycling process of the system being discussed. Through these processes, ideas for how this could be applied in a curriculum are learned, and a brief outline of a possible curriculum is offered, followed by a section on how the MASEE program helped me as a teacher. The intention of this research is to give teachers an idea of what a high school capstone design project focusing on aquaponics could look like.

Chapter 2

Literature Review

In 2009, the National Academy of Sciences published a report that outlines various topics related to engineering in K-12 education. The report itself was written by several panels of experts from various fields, including The National Academy of Engineering, the Board of Science Education at the Center of Education, and the National Research Council. To date, much of the effort to improve STEM education has been focused on improving science and mathematics education. The technology and engineering portions of the STEM equation have had little to no attention for improvement in grades K-12. Prior to the current state of engineering education, most of the focus in the literature has been on post-secondary engineering studies. However, in the past fifteen years, some form of formal engineering education has been “slowly making its way into U.S.K-12 classrooms.” (National Academy of Engineering 1) Although the report details the current state of engineering education and how it can be improved, it does acknowledge that some questions remain unanswered. A few examples that are relevant to this research are:

> “How does engineering education “interact” with other STEM subjects? In particular, how has the K-12 engineering instruction incorporated science, technology, and mathematics concepts, and how has it used these subjects as a context for exploring engineering concepts? Conversely, how has engineering been used as a context for exploring science, technology, and mathematics concepts?” (National Academy of Engineering 2)

The “interaction” that the report is referring to is often called integration in the realm of education. Integration itself is fusing together the content from more than one subject, such as learning mathematics in an engineering project, or learning science in a mathematics project. It may seem straightforward to integrate a project to do this; however, in the context of engineering education, “the goal of truly integrating STEM is challenging.” (Berland 1) In fact, currently in the U.S. “in most elementary and secondary schools, STEM subjects are taught with little or no connection among them.” (National Academy of Engineering 16) Curricula in the United States have evolved by separating subject areas, so that we teach mathematics in mathematics classes, science in science classes and so on. Coupled with the new push of standardized testing and accountability, there is little room left for integrating subjects in order to see connections to other content areas, due to the fact that a stringent menu of concepts must be covered for the standardized test at the end of the year. The NAE report ultimately ends with calling for a new way to think about STEM education as a whole. “The teaching of STEM subjects must move away from its current siloed structure, which may limit student interest and performance, toward a more interconnected whole.” (National Academy of Engineering 167)

There is little doubt that STEM education is in need of an overhaul, but until that can take place, the focus of integration ought to be placed in the engineering classrooms that are emerging in the United States. Typically, these engineering courses in K-12 education are categorized as Career and Technology Education, or CATE, which generally translates to a technical elective course in a high school. It would be pertinent to define engineering and technology as they relate to the STEM equation. From the NAE report Box 1-1,

> Technology comprises the entire system of people and organizations, knowledge, processes, and devices that go into creating and operating technological artifacts, as well as the artifacts themselves. Throughout history, humans have created technology to satisfy their wants and needs.
>
> Engineering is both a body of knowledge –about the design and creation of human-made products- and a process for solving problems. This process is design under constraint. One constraint in engineering design is the laws of nature, or science. Other constraints include such things as time, money, available materials, ergonomics, environmental regulations, manufacturability, and reparability. Engineering utilizes concepts in science and mathematics as well as technological tools. (National Academy of Engineering 17)

By looking at these definitions, one can see how the two are related. Technology employs the "knowledge, processes and devices that go into creating and operating technological artifacts" while engineering is "about the design and creation of human-made products and a process for solving problems." For this reason it makes sense that an engineering course at the secondary level would be placed in a CATE setting. The other STEM components, science and mathematics are also necessary for the comprehension of knowledge in engineering because many of the foundations in engineering courses are so deeply rooted in those concepts. "Scientific knowledge informs engineering design, and many scientific advances would not be possible without technological tools developed by engineers." (National Academy of Engineering 27).

In addition to listing integration as something essential in engineering education, the NAE also framed three principles for K-12 engineering education. First, "engineering education should emphasize engineering design." (National Academy of Engineering 151) This research reported here is relevant to this idea because it is meant to be a design challenge in which students are going to design, build, and maintain an aquaponics system. During this design project, with a focus on generating multiple solutions and iteration to fully optimize, students will be exposed to designing and maintaining a system, which are all described as important to engineering design by the NAE (National Academy of Engineering 151). The second principle offered by the NAE is that "K-12 engineering education should incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills." (National Academy of Engineering 151) This should also be applied in the curriculum for designing the aquaponic system, with regard to modeling and data acquisition, which are both included in the curriculum. Lastly "K-12 engineering education should promote engineering habits of mind." (National Academy of Engineering 152) Engineering habits of mind is an interesting concept because engineering is far too often simply associated with science and mathematics. Engineering habits of mind, however, include an array of abilities such as "systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations." (National Academy of Engineering 152) As this problem is framed, as noted in the introduction of this report, ethical considerations play a large part in framing this project to a high school student. These elements and foundations outlined by the NAE are woven into the curriculum for this project.

There is no doubt that all of the elements of STEM are connected; however, why is it so difficult to integrate subjects that are so seemingly interconnected already? As mentioned earlier, although it is not the focus of this report, the politics involved with accountability, data tracking, standardized testing and the like prevent progressive models of teaching STEM that are not siloed. In my personal experience, it is much more productive to introduce integrated projects in non-tested subjects. On a more technical note however, the focus of this research is *how* STEM subjects can be integrated, the benefits of integration, particularly with regard to building an aquaponic system, and how the curriculum relates to the goals outlined by the NAE.

Berland (2012) outlines four specific criteria for designing the STEM based activities for the course *Engineer Your World*. They are defined as follows. “The challenge must have multiple solutions… the challenge will require students to consider the problem from multiple engineering disciplines, the challenge must address a societal need, and the challenge must directly draw upon math and science content.” (Berland 5) Designing an aquaponic system can bring all of those elements together into one project. Berland also suggests that students may “be able to design and build the specified product successfully without developing an in-depth understanding of the relevant science concepts.” While this has yet to be determined because it has not been tested, my experience indicates that this could be the case, and can be an issue when doing hands on activities that do not explicitly deal with the mathematics or science content that the instructor is trying to teach. In other words, the end goal of this project is to design an aquaponic system which is interesting to the students. The mathematics and science learning goals will surely not be as important to a high school student as designing and building something. This must be kept in mind while designing a curriculum for design challenges and proves to be the fulcrum of the curriculum offered at the end of this project.

The learning theory behind such a project like this is called situated learning. The situated perspective, or situativity, is the idea that learning takes places through context, which "is meaningless for the learning if the learner is not engaged in interactions and activity." (Johri and Olds 163) Also, "any higher-order cognitive function is the result of social interactions.' (Johri and Olds 164) Activities and collaboration in communities of practice guide learning and give the learner perspective on what they are trying to learn. These "actions and activities are guided towards a larger goal and learning is about understanding that larger goal and aligning actions with that." (Johri and Olds 165) In the development of a curricular unit, these ideas of learning should be incorporated, such that activities require collaboration, and are working towards a larger goal that is understood by the learner.

By integrating multiple subjects together through relevant activities and social interactions, engineering education can forward the goal of keeping more students interested in STEM subjects. With a newfound focus on K-12 education, engineering education ought to foster learning with the less focused on traits of engineering, such as engineering habits of mind, as well as mathematics and science content, in order to enhance student learning. Engineering design is a key concept to develop these abilities, which is the inspiration for this project.

Chapter 3

Design Process

As with every design based challenge, a design process was loosely followed. By no means am I an expert on this, but since I have completed several projects before using the design process, I followed the progression of logic involved in the process and designed something that worked for my environment. Engineering courses in high school tend to have some kind of design element in them, in order to spur interest in engineering during post-secondary study. This focus on design, and the engineering design process, is not only a goal of the NAE, as aforementioned, but is prevalent throughout high school curricula. For this project, I say that I "loosely followed" a design process, because the design process itself is really just a progression of logic and documentation. First I conducted extensive research on aquaponics, particularly relying on "Aquaponic Gardening – A Step by Step Guide to Raising Vegetables and Fish Together" by Sylvia Bernstein. I recommend that anyone interested in this project read this book first. It is a crucial resource for design, constructing, cycling, and maintenance. After I felt I had a grasp on enough of the information, I read online blogs and forums, such as (Backyard Aquaponics: A Place to Discuss Aquaponics), (Discussion Forum), (Hallam), and (Affnan), about users and their successes and difficulties, which also helped me in the process. This research informed the design decisions that were made in constructing my system.

The first step in the design process was determining the actual problem to be solved. Since this is something I have read about and believe in, I understand the problem at a global level, and translated that to my local level with regard to conservation of water and food production. I want to grow food for my family, and do it using less water. The next step was identifying the constraints. Personal constraints included budget, aesthetics, orientation, and time.

Personal constraints included keeping the project under $3,000. I also wanted to complete the building portion of the project by March 1, 2014, and I wanted it to look nice in my backyard. Aesthetics are subjective, and the only persons I had to satisfy were myself and my wife. The system must face south so the plants can receive the maximum sunlight during the winter months. The angle of inclination of the sun during the winter months is roughly 36 degrees in Austin, Texas. This in turn will limit the amount of sunlight the crops will receive during that time. Also the literature indicates that flood and drain aquaponics systems are the most simplest to construct and design. There are many different types of aquaponics systems; however, since I am a novice and have never done this before I did not want to venture into designing and building a more complex system, at least during the first time. Thus, I constrained myself to building a basic flood and drain system.

Ultimately there are three main components to consider when designing a flood and drain aquaponic system: the fish tanks and grow beds, the plumbing, and the configuration. If I were to start over I would probably start with the configuration, since that seems to inform the other two. While designing my system, however, I focused more on pushing the limits of the system and its optimization based on the work of

(Endut 2010), rather than focusing on the actual system itself, and how it could be practically constructed given the space and materials I had available. This in turn took up much of my time before I even began constructing, and as a result, I missed my March 1 deadline for completing the construction of the system. Also, spending time trying to “find the science and math” slowed down the project.

Figure 1 below, shows a diagram of the basic components of a media based aquaponic system. Although there are many different configurations for media based systems, this is the basic design diagram used for the basis of my design. Water is pumped from the sump tank, to both the fish tank and growbeds. As water in the fish tank rises, an overflow pipe that spans to the bottom of the tank, forces fish waste and water back over to the sump tank. The water that flows into the growbed, reaches a maximum height, determined by the “autosiphon” or bell siphon, then drains back to the sump tank.

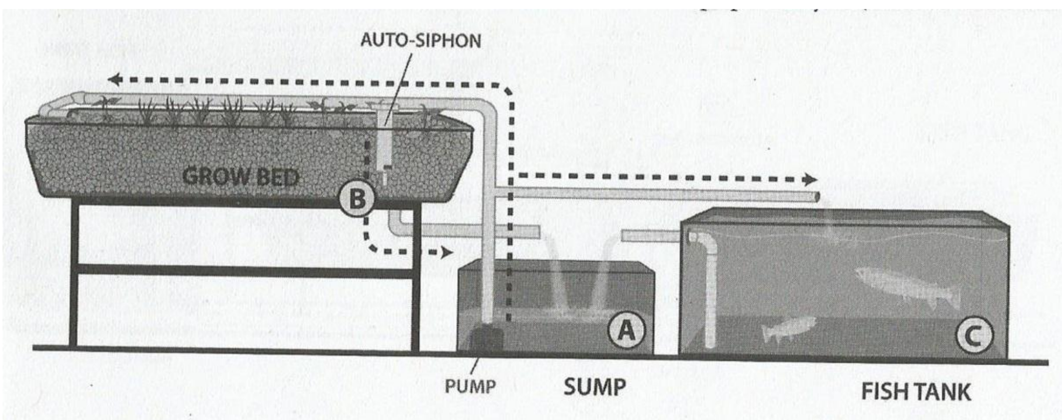

Figure 1: Media Based Aquaponic System Layout (Bernstein 60)

The components of the system all perform vital functions. The fish tank not only houses the fish, but dictates the size of the rest of the system. The volume of this tank constrains the amount of fish and fish waste that can be present in the system, which determines the size of the growbeds. The growbeds hold the grow media as well as the plants. However the grow media itself provides the surface area that the bacteria need to colonize and process the fish waste with the help from worms. The entire biological filter is housed in the growbeds, which makes aquaponics work.

The plumbing encompasses all of the lines that transfer the water from the sump tank to the fish tank and growbeds. It also includes the bell siphon, which eliminates the need for a timer on the pump. The bell siphon has four main components: the standpipe, bell, media guard, and water break. Below, in Figure 2, shows how these components are arranged within a growbed.

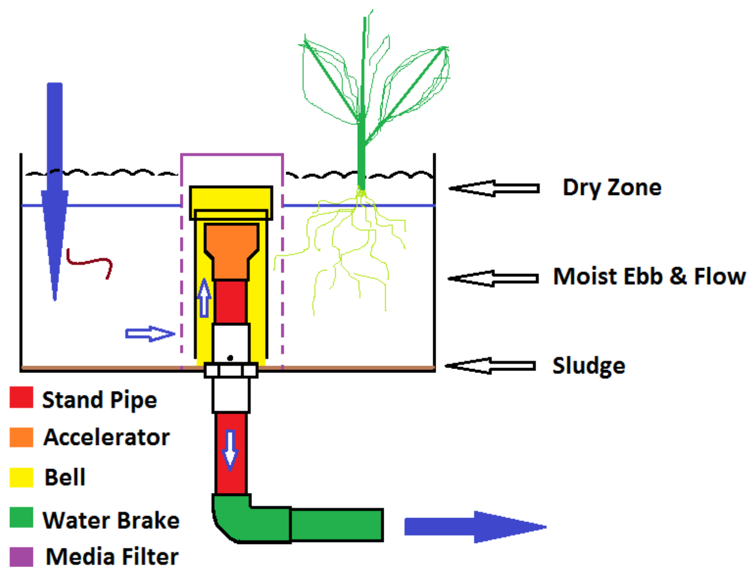

Figure 2: Bell Siphon Components (Source: http://aquaponics-system.com/wp-content/uploads/bell-siphon.jpg.png)

3.1 Initial Calculations

My design was informed by research conducted by a student at McGill University, that addresses the non-scientific approach of aquaponics farmers in Barbados, and attempts to optimize several aspects of these systems. (Connally) Based on this, I focused on the Hydraulic Loading Rate (HLR), which determines how much water flows into the grow beds from the fish tank in a given day. The units are ft/day. This in particular was the most important facet to me, since the majority of the production of food will be coming from the growbeds. Although there will be fish to harvest, in comparison to how long it takes for plants to mature versus how long it takes fish, it is much more beneficial to focus on plant growth. The hydraulic loading rate is given by

$$HLR = \frac{Q_W}{A_G},$$

where Q_W is the flowrate from the pump, and A_G is the area of the growbeds. According to Endut et al. (1516), the optimum HLR for plant growth is 1.28 m/day, which is 4.20 ft/day. Given the area of my backyard, 64 ft^2 of grow bed area is a good size. Another factor to be considered was Hydraulic Retention Time (HRT), which is the amount of time measured in minutes that the water stays in a growbed before draining. This is given by

$$HRT = \frac{A_G * h_W * \Phi}{Q_w},$$

where A_G= surface area of the growbed in ft^2, h_w = maximum water height of the growbed in ft, ϕ is the porosity of the grow media (unitless), and Q_W is the flowrate of the water in ft^3/hr. According to the research done by Endut et al., the optimum removal of nutrients from the plant roots occurs when the flowrate is 1.6L/min, which is 25.36 gal/hr. For the calculations themselves, an Excel spreadsheet was created, to use the Solver add-in to find the values for flowrate, surface area, height of the water inside of the beds, etc.

Bernstein (107) states that, as a rule of thumb, the flow of water should recirculate at least the entire volume of water of the system through the grow beds every hour. This ensures that there is proper bio-filtration for the fish. As another rule of thumb, depending on the configuration, the total volume of the grow beds should at least be a 1:1 ratio with the volume of the fish tanks, but can be pushed to 2:1 or even 3:1. I wanted in my system to push this limit. The volume of the fish tanks is typically simplified in aquaponics due to the fact that the grow beds themselves should be 1' deep to allow for the multiple zones within them. There is a dry zone, at the top of the bed as a sunlight buffer, a root zone below that, which will be constantly flooded and drained, and a mineralization zone at the bottom, where there is a thin 2" area that is always wet. Because the growbeds are typically 1 ft deep, grow bed volume is typically simplified to grow bed area. So, with a 64 ft^2 grow bed area, I should have at the very least, a 32 ft^3 (240 gal) fish tank volume. So based on these rules of thumbs, I would need a fish tank of about 240 gallons, and a flow rate of at least 240 gallons per hour. However, the optimization program would not allow for that large of a flowrate. It was impossible to have that flow rate and still be close to the optimum HLR or flowrate. In fact, to get the flowrate and HLR near their optimum values, I had to change the volume of the fish tank as well as grow beds to even come close. Below is the table that got the closest to the desired values after a lot of iteration.

OPTIMIZATION OF AQUAPONIC SYSTEM CALCULATIONS				
Variables	**Values**	**Gallons (Growbeds)**		
V_G = Growbed Volume (ft^3)	25.6	191.488	**Grow Bed to Fish Tank Ratio**	1.896296296
A_G = Growbed Surface Area (ft^2)	64	**Gallons (Fish Tank)**		
V_f = Fish Tank Volume (ft^3)	13.5	100.98		
h_w = Height of Water in Grow Bed (ft)	0.4			
ϕ = Porosity of Grow Media	0.42	**Gallons**	**HLR = Hydraulic Loading Rate (ft/day)**	5.0625
Q_w = Water Flowrate (ft^3/hr)	13.5	100.98	**HRT = Hydraulic Retention Rate (Min)**	47.78666667
			Optimum HLR =	4.199475066
Gallons per hour flowrate gal/hr	100.98			

Table 1: Optimization Calculations

These values are still not very close to the optimum HLR. Another issue with these calculations is that the height of the water in the grow beds is much lower than recommended. In the design of Connally (2010), the water in his beds was only 5 cm, which may have been because he was using coconut husk as his grow media, rather than shale, or expanded clay. At this point, I realized I needed to collaborate with people who have done it before, and ask them if they knew anything of the sort about HLR, and flowrates.

In particular, I contacted Shaun Bishop of Third Coast Horticulture (Austin, TX), about these values. He focuses on practical aquaponics and instead, recommended the rules of thumbs in (Bernstein). Based on this discussion, I decided to ignore these values in the program, and instead build a system that would work.

3.2 Concept Generation and Selection

Next in the engineering design process is generating concepts. This was going on in the background as the initial calculations were being developed. A general rule of thumb for this, is that quantity is needed so that the quality can be chosen as a concept to move forward with.

An early concept was designing a modular system inside of a shipping container. See Figure 3 for a general idea of the concept. This design allows multiple systems be set up next to each other, or stacked on top of each other. A person can walk in the doors, and on either side of the shipping container, rafts are fixed to the walls. In the back of the containers, a fish tank large enough for all of the rafts supplies all of the water to the rafts. Lights hang under each raft to illuminate the plants, and the entire structure is insulated and temperature-controlled with a HVAC system. This concept was rejected for multiple reasons. First, I did not want an old shipping container in my backyard. It also would be extremely expensive to retrofit the inside of the shipping container to maintain a set temperature and supply all the lighting needs for the plants. Lastly, it would require a deep water culture to work, rather than a media based system, which was one of my constraints. Ultimately, this was not an idea fit for the space it was to occupy, and would have broken all three of my constraints, especially the price, and time.

After rejecting this concept, I focused on viable materials available both locally and online that fit the budget. All of the materials must be food safe to prevent harming the fish (Berstein 72). The materials must be chemically inert, and since this system was going to be situated outside, the materials must be resilient to the elements. For initial concepts the entire system is made out of wood, and covered with duraskrim, a thick

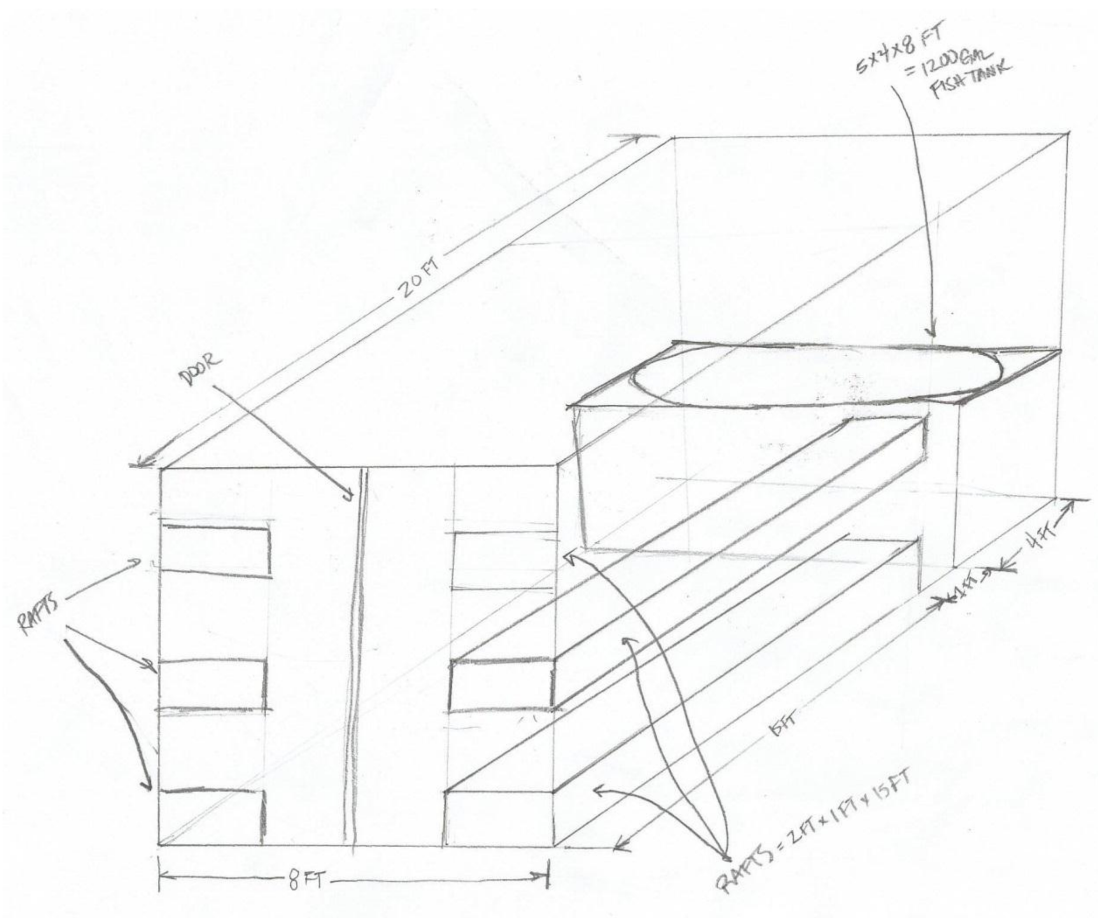

Figure 3: Shipping Container Design Concept

plastic that is chemically inert. These concepts were rejected because of the considerable amount of time needed to construct the beds out of wood, and the possibility of the wood rotting over time. As shown in Figure 4, the concept has two large growbeds, each 3’ x 12’ built out of wood. The two would be staggered in height, to maximize sun exposure during the winter months. Underneath each of the growbeds, is the fish tank and sump tank, which are shaded, to minimize algae growth. A PVC structure is placed over the top of the beds to support a cover, either a shade cloth during the summer months, or clear plastic during the winter months to create a greenhouse effect. The goal of this design is simple: maximize the sunlight during the winter months to grow food, as well as minimize the space required to do so. With the sump and fish tanks situated underneath the grow bed area, the plumbing is compact and fits entirely underneath the growbeds. Also, the fish and sump tanks are sunk into the ground, to provide insulation in the hot and cold months. Tilapia (the fish of choice) must have a water temperature between 60° and 95°F (Bernstien 142). By situating the beds over the tanks, as well as sinking the tanks into the ground, the water should stay relatively cool during the summer, and warmer than the ambient air in the winter.

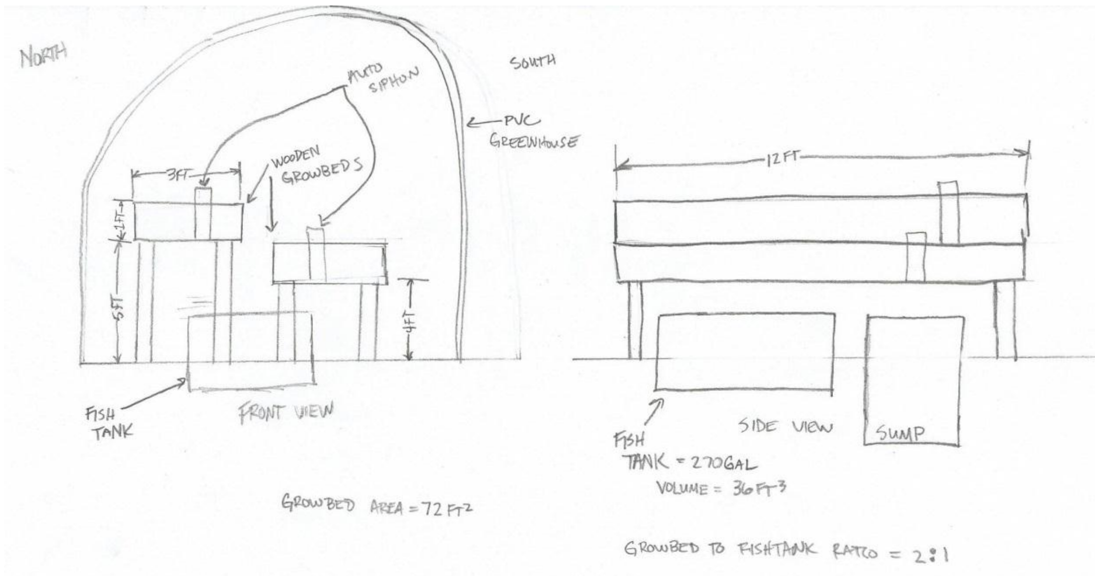

Figure 4: Wooden Bed Concept

Concerns about this concept range from accessibility to whether the back bed will get enough sunlight. Additionally, there is a concern over distribution of nutrients, since the water was to be fed to the top growbed first, then gravity flows to the second growbed. Also, the plumbing is complicated compared to other concepts.

The next concept was derived with the help of people experienced with aquaponics (Third Coast Horticulture). Based on competitive pricing and convenience, and ultimately timeliness, I decided to source my equipment from there. Also, inspecting operating systems and analyzing their components was much more beneficial than reading about them in a book. Third Coast Horticulture has several demonstration systems, with 4’ x 4’ growbed, and a 110 gallon fish tank. Each of their systems have bell siphons, and the plants they had growing looked magnificent.

I decided to incorporate their growbeds as well as tanks. A grow space of 64 ft^2 requires four of their growbeds. The system also requires a larger reservoir of water for the fish. Third Coast sells 180 gallon tanks and 110 gallon tanks, both LDPE (low density polyethylene) and food safe. I chose a rectangular array for the growbeds, where the user can walk in between them to tend to the plants. The fish and sump tanks are situated such that the sump tank is under one of the beds, and the fish tank adjacent to it. An overflow pipe connects the two tanks, such that when water flows into the sump tank, it is transferred to the fish tank, backfilling the water being pumped to the beds. Figure 5 shows the idea in a rough sketch.

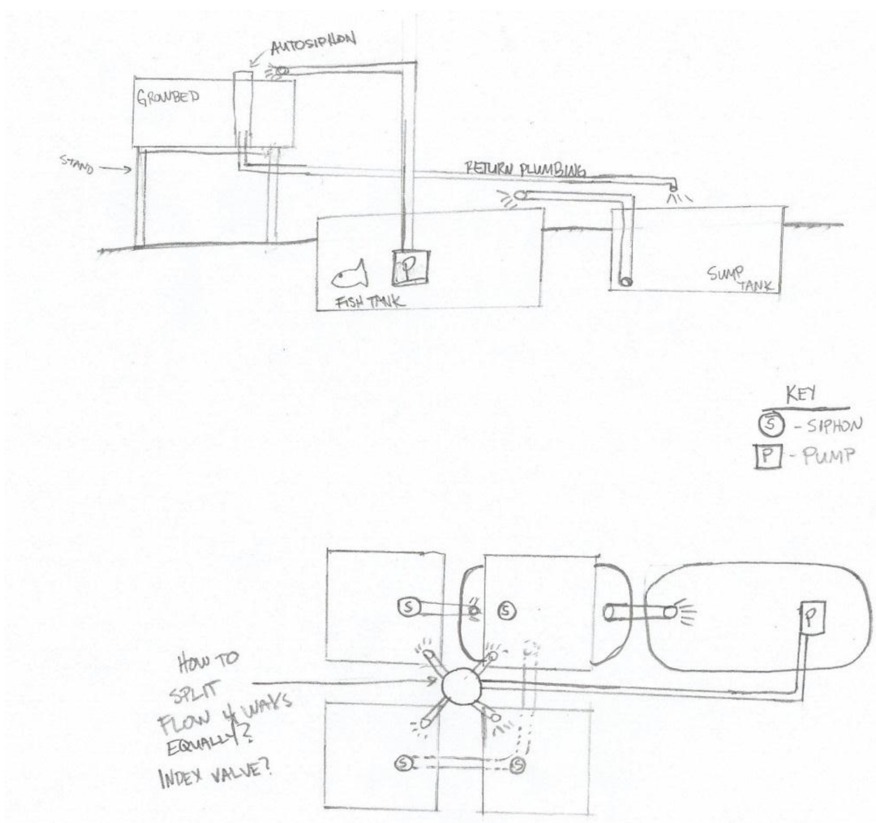

Figure 5: Rectangular Array Design

To distribute flow evenly into the growbeds., I designed a cylindrical reservoir, situated in the center of the four growbeds. The reservoir has drain holes drilled at the same level around its circumference, and the water level inside the contain remains constant, at a certain height above the outlet holes (See Figure 6). Using Bernoulli's Principle the water height needed to provide a 25 gph flowrate was calculated.

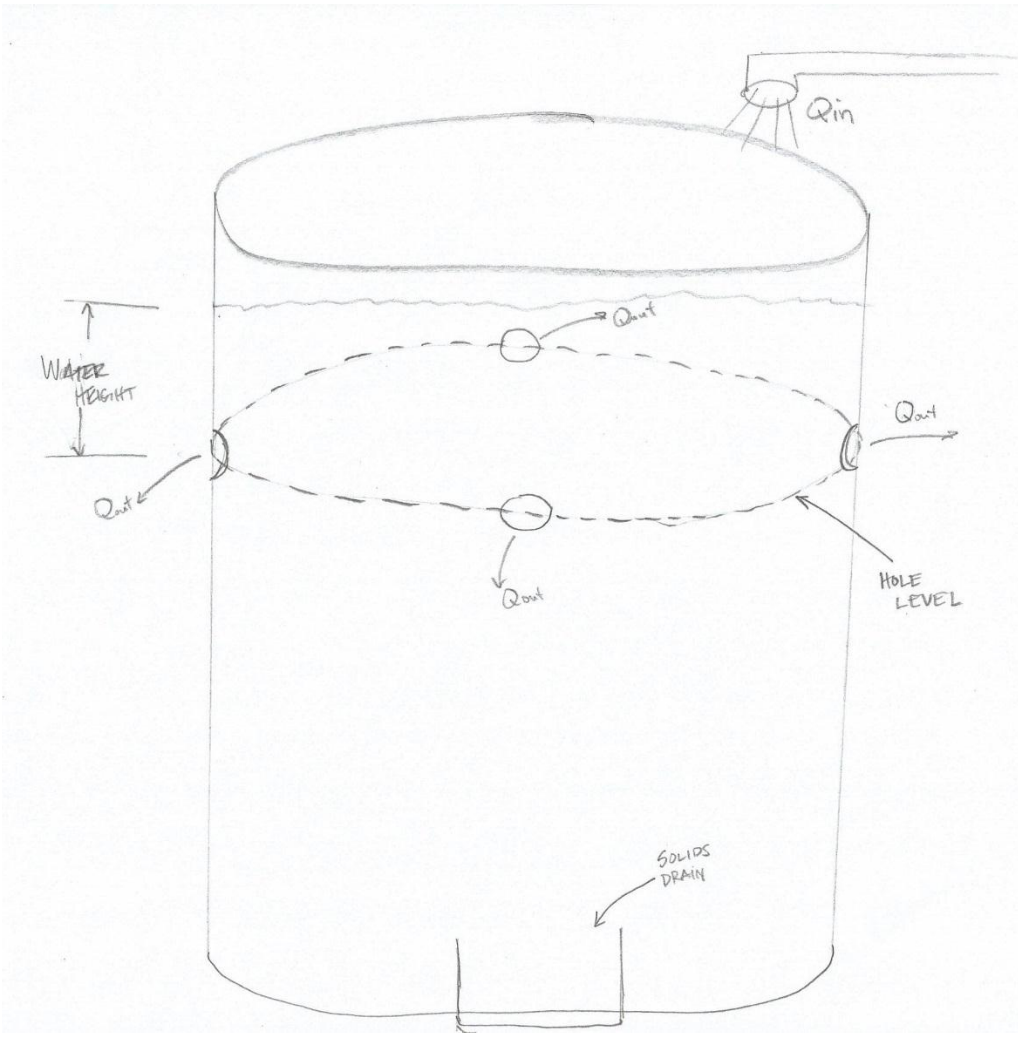

Figure 6: Split Water Flow Idea

However, this concept requires the reservoir to be situated in the center of the array, and all growbeds must be at the same height for this to work. Since my backyard is not level, this is not practical. An easier solution to this problem has a discharge line from the pump run underground between the growbeds. Riser pipes with control valves are run to the growbeds. The valves are used to adjust the flow rates to the beds.

In my initial concept I configured the system to pump water directly from the fish tank to the growbeds to provide the best filtration of the fish waste and to propagate it evenly throughout the system. However, this configuration ultimately limits the number of fish that can be stocked in the fish tank due to varying levels of water. The final design is based on the CHOP (Constant Height One Pump) and CHOP2 systems from (Bernstein).

The final design keeps convenient elements from previous iterations while including configuration features that I had previously overlooked. I purchased four 4'x4' ABS plastic growbeds to create the desired 64 ft^2 of grow space. I also selected a 180 gallon fish tank and a 110 gallon sump tank, both LDPE. Both ABS plastic and LDPE are food grade and do not leech toxic elements that might harm the fish. The configuration is based on the "CHOP2" layout, which was introduced in 2011 by Murray Hallam, with one difference. (Bernstien 60) In the Hallam layout, water flows from the sump tank to the growbeds and fish tanks simultaneously. When the growbeds fill up and activate the bell siphon, water drains back to the sump tank. An overflow pipe situated in the fish tank, forces water through a pipe at the bottom back over to the sump tank. This configuration is beneficial to the grower, because it allows for a higher growbed-to-fish tank ratio due to the fact that water from the sump tank backfills water pumped out of the fish tank, and the water level in the fish tank never decreases. A great animation of how this works can be found at http://practicalaquaponics.com/blog/aquaponics-chop-mark-2-operating-system/. This configuration allows for expansion of the system and less of a chance of system failure due to pumps failing since only one pump will be required instead of two; any pump failure will cause the system to fail. I altered this design to pipe the water from the growbeds back to the fish tank, rather than the sump tank. A final sketch of my design can be found below (Figure 7).

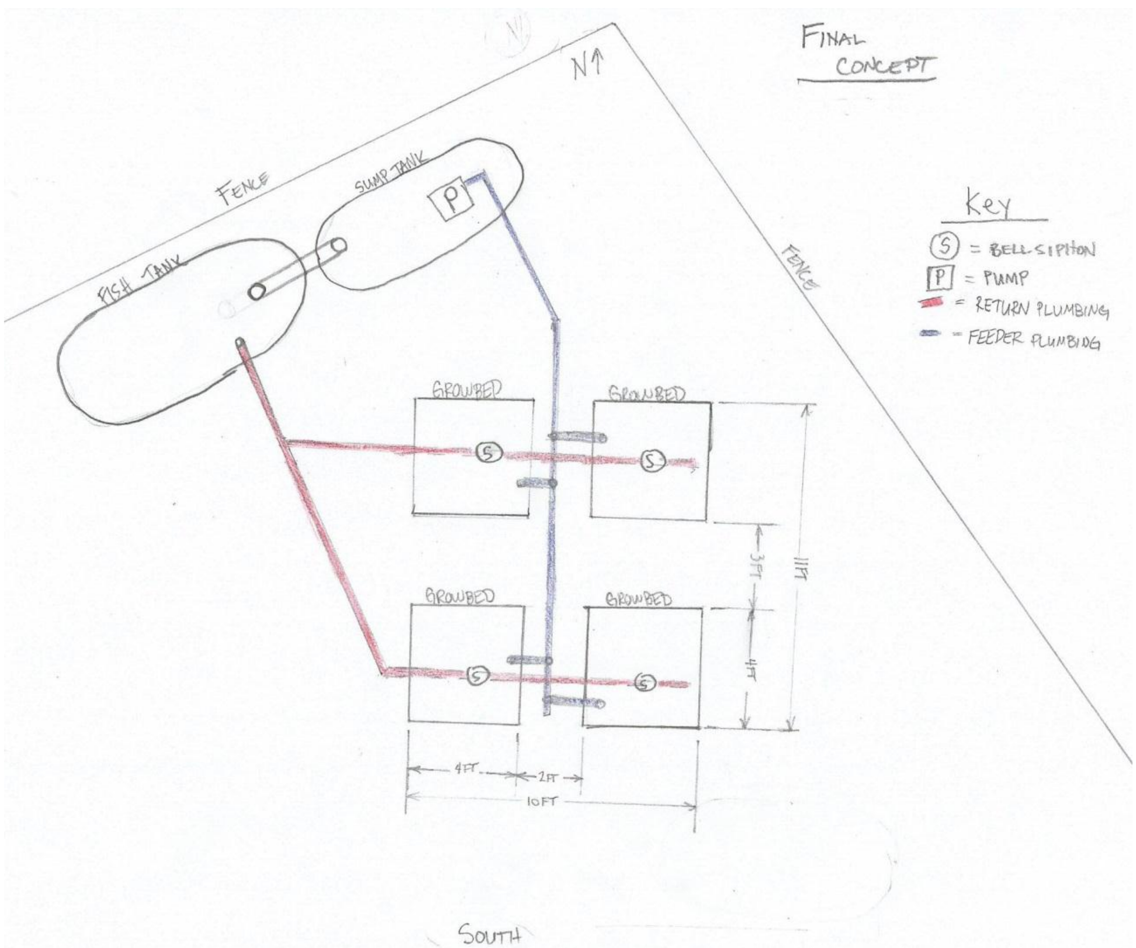

Figure 7: Final Design Sketch

The back corner of my yard provides the most sunlight, and has an area where the beds can be oriented south. The PVC line from the sump tank runs underground to the four beds, and is piped up from the ground and over with a valve to regulate the flow. Underneath the growbeds, there are PVC return lines, that are piped together and flow back to the fish tank. As water flows over the level of the overflow pipe connecting the fish and sump tanks, water is forced over to the sump, completing the cycle of water. The sketch in Figure 7 is overly simple and does not reflect the other decisions that had to be made, such as the sizing of the pipes to the growbeds, sizing the pipes on the return to handle the flow from the siphons, the siphons themselves and their dimensions, selecting the correct pump for the desired flow, and selecting the correct size of pipe between the sump tank and the fish tank.

To account for head loss and the diversion of the flow four different ways, I selected a 1500 gph pump. I initially thought that the pump would be too large; however, it is easier to dial down pump flow with valves than it is to increase to a flowrate that the pump is not capable of. The sizing of pipes was determined by the maximum diameter (1") of the pump itself. The PVC lines to the growbeds are 1½" in diameter, and are reduced as they rise vertically to ¾". The stand pipe in the siphon system is 1" diameter. Since these were to be in line with one another, the return pipes are increased to 2" diameter.

3.3 Summary

This chapter describes many of the iterations and design decisions made during the design of the aquaponics system. After selecting a final concept, I began prototyping my design, which is the final stage of the design process. This prototyping process was iterative. Since the scale of this project is so large, upgrades and changes were constantly needed to tweak the system to ensure that it runs smoothly. These issues are discussed in detail in the next chapter.

Chapter 4

Construction Process

This chapter describes the process of building my prototype aquaponics system. A bill of materials can be found at the end of this report in the appendix. Unless you have had the experience to build and construct something before you design it, the design seldom comes exactly how you planned it on paper. Although I had a rough idea of what the system was going to look like, and it does look similar to that design, when building something like this things get simplified and or omitted and changed in order to improve functionality. I am sure the next system I design and build will be easier to plan and build, and I will have a better understanding of critical components of the systems that make this process work.

First I constructed the metal leg frames that the growbeds sit on. I bought these pre-cut from Third Coast Horticulture. Each of the four stands includes two 33”, four 38 ¾”, and four 28” galvanized steel pipes, all with a 1 ¼” diameter, along with speed rail fittings to connect them. An allen wrench was used to tighten all of the rail fittings (See Figure 8). The speed rail fittings are arranged in the picture in the same fashion as they are on the stand in Figure 9.

Figure 8: Speed Rail Fittings

Figure 9: Constructed Stand

To construct these, first place the speed rail fittings on the 33" long galvanized steel pipe. This is best that this is done on a level surface, so that the fittings can be placed upside down and be level when they are tightened. Use an allen wrench to tighten the fittings, but do not fully tighten until the entire structure is leveled. Next insert the four 38 ¾" steel galvanized pipes into the four speed rail fittings. Lightly tighten them to hold in place. Repeat the first step on the other 33" steel galvanized pipe but do not tighten. Once the fittings on are on, fit the protruding steel galvanized pipes into the speed rail fittings, and lay flat on the ground. Check that the assembly is level. If level, tighten the remaining fittings with an allen wrench. There should be four openings facing upward, which the 28" pipes will be inserted into. Tighten the fittings after all four are placed inside the openings. Lastly, place the speed rail bottoms on the ends of the pipes, and tighten as well. Afterwards, make sure all fittings are tightened and flip the entire structure over to check for level. If level, repeat the process for the other three stands. If not, adjust the feet.

Figure 10: Completed Stand

Figure 11: Stand with Growbed

The next step was to dig the holes for the fish tanks. I had to change the plumbing layout to avoid existing piping in the yard. I did however, keep the 2 x 2 rectangular array pattern.

I placed the reservoirs on the ground and marked the perimeters with wooden stakes to provide guides to digging the holes to the correct size. I dug approximately 2.5’ down for the entirety of the tanks, and checked to see if they fit inside the holes. Given the landscape around my house, rocks were an issue, and a pickaxe was used to remove them from the ground. The holes in the ground do not reach the top of the reseviors. I wanted to leave a little room at the top to prevent any rainwater from entering the system. After I dug to the desired depth, I used sand to level the holes to prevent any dead zones where water would not flow inside the tanks. This was a trial-and-error process: a lot of digging, placing the tanks inside the holes, and checking to see if on the bottom, as well as around the edges were level. To do this I used a 2’ level and repeated this process until I was satisfied with the level of the reservoirs.

Figure 12: Fish and Sump Tanks in Ground

Next, I focused on situating the stands in the backyard. In my plan, I devised a way to have them arranged in a 2 x 2 rectangular pattern. It fit well when I laid them out and seemed reasonably close to the fish tanks. By keeping the stands and the reservoirs in a relatively close proximity, the return plumbing was minimized. The stands themselves are situated 44” away from each other in the north-to-south direction, and 32” away from each other in the east and west directions.

After arranging the stands, I then laid the 1 ½” PVC line in the ground from the sump tank to the growbeds. Using a pick axe, I dug 6” into the ground on the line where the line was going to lay. I then placed the PVC pipe next to the hole to ensure that the components would work. Three 10’ sections of 1 ½” pipe, one 1 ½” coupling, two 1 ½” 90° elbows and four 1 ½” tees were used. First, one of the 90° angle elbows was glued to the end of a 1 ½” x 10” pipe, and placed 8” from the sump tank. This section was eventually plumbed to face upward from the pump in the sump tank. A 1 ½” x 1 ½” coupling was then glued on the other end of the 10’ pipe. Next, a 1 ½” pipe was cut to 1’ length, and dry fit on the other end of the coupling and on the other end of the 1' pipe, another 1 ½" 90° elbow was dry fit on, facing towards the growbeds. Using the same pipe the 1' section was cut from, another 46" cut was made, followed by three 6" cuts. Using another piece of 1 ¼" x 10' pipe, another section was cut to 84" length. To assemble the rest of this section, I dry fit the 46" pipe into the 90° elbow such that it vertically (north to south) bisects the 2 x 2 array. Then I slipped a 1 ½" tee on the end of the 46" section. These tees face upwards to supply the growbeds with water. Next, I dry fit one of the 6" sections that were just cut into the other end of the tee. On the other end, I added another 1 ½" tee, again making sure that it is faced upwards. After that, I placed the 84" section of pipe on the end of that tee, followed by the 6" section, then another tee, then another 6" section. At the end of the last 6" section I placed a 1 ½" end cap. Once all of these were laid in line with the hole that was dug between the stands, they were glued together. See Figures 13 and 14.

Figure 13: PVC Line to Sump

Figure 14: PVC Line to Growbeds

Once the pieces were glued together and the line was in the hole, I covered the pipe with the dirt that was dug out. Then I glued in 1 ½" x ¾" PVC bushings into the tees. Dirt was moved all around those, and bottles were placed upside down to prevent debris from falling into them as the project was getting finished. Figure 15 shows the tee as well as bushing with the end cap, and Figure 16 shows all of this completed on the site.

Figure 15: PVC Feeder Line Bushings

Figure 16: Site with Feeder Plumbing

One issue that complicated the prototype was the grade of my backyard, which slopes gradually towards the house, so the ground is not level. Since the growbeds have to be level to ensure an even level of water inside of the growbeds, I used 16 concrete blocks to level the stands. The concrete blocks are 4” tall x 8” wide x 16” long. Each foot of the stands is placed on top of one of these blocks. I marked their locations by placing the blocks next to the stands and marking them with a wooden stake. The placement did not have to be exact, due to the large area of the blocks.

I sunk each block into the ground with the top still above the ground. This process took a lot of time, due to the fact that each block had to be leveled, then each block in the set of four (where each leg of a stand would sit) had to be leveled relative to the others in order to ensure that the water level is even with the bottom of the growbed. To do this, I sunk and leveled the first block lengthwise and widthwise using a 6” level. After the first block was leveled in all directions, the next block leveled the exact same way, except a 2’ level was used between the blocks, to ensure that the second block was completely level to the first. The process was then repeated for the last two blocks. The difficult part of this was that when leveling each block relative to the others, any little tweak on one block requires changes to the others. Thus, the level of each subsequent block was related back to the first block. I leveled the blocks for one stand at a time, and then repeated the process for the other 3 stands. After I was finished leveling the blocks, to check my work I placed the stands on top of the concrete blocks and checked their level (both lengthwise and widthwise). Afterwards, the growbeds themselves were added to ensure they too stood level on the stands. See Figures 17 and 18 for two completed perspectives.

Figure 17: Stands Level on Site 1

Figure 18: Stands Level on Site 2

Before any holes were drilled in the growbeds, the bell siphons had to be constructed out of PVC pipe. Bell siphons provide a way to drain the growbeds without the use of a timer, which causes unnecessary wear on a pump due to constantly turning it off and on (Bernstein 101). This is an important part of the system because it determines the maximum water height within the grow beds. Rather than adhering to the calculations above, I instead went with the rules of thumb outlined in (Bernstein). The four stand pipes, are constructed from 1" PVC pipe cut to a length of 10". The "bells" that sit over the stand pipe are constructed from 2" PVC pipe and are 10 ½" tall. Finally, the media guards are constructed from 4" PVC pipe cut to a 13" length.

To assemble the bell siphons, I dry fit the 10" sections of 1" PVC pipe into a Botanicare 1" bulkhead slip x thread fitting. The 2" PVC pipes were then drilled with a 1 ½" hole saw drill bit three times around the bottom pipe. These holes let water flow to the fish tanks during the siphoning action. At the other end of the 2" pipes, a 2" slip x female adapter was glued on, and a cleanout plug was screwed into the top.

Below, shown in Figure 19, are the completed bell components, the 1" stand pipes attached to the bulkhead fittings, and the 1" elbows, which are 1" PVC x 12" long, with 1" 90° elbows glued on the ends. Not pictured are the media guards, which are the 4" sections of PVC pipe that were cut to 13" length. To finish these, an array of holes was cut around the pipe, using a chop saw. There was no set number of holes around them. To do this, very carefully hold the 4" pipe with one hand, and slowly make cuts into the pipe. Do not go far, as each of the slices made with the blade only needs to be 3" – 6" in length. None of the incisions should penetrate directly through the pipe and enough should be made such that the media stays out, and the water flows through. These are situated on the outside of the bells, in the siphoning system.

Figure 19: Bell Siphon Components Assembled

At this point, I tested the bell siphons to make sure that they drained properly, and that they stop draining despite water still flowing. To do this, I drilled holes into the growbeds at the proper locations. The first hole, 1 ¼" in diameter, was drilled 24" from the north end of the bed, and 17" from the east side, closest to where the other growbed sits using a hole saw. I also drilled an additional 1" hole for an overflow safety,   10" from the siphon towards the inner side. The holes for the bulkhead fittings may vary depending on brand. I matched a hole saw drill bit to the bottom of each of the bulkhead fitting, and used that to size the holes. Next, I placed the 1" bulkhead fitting that was fitted with the standpipe in the center hole, and another Botanicare ¾" tub outlet in the other hole. Silicone was added around the bottom of each of the fittings to prevent leaks (see Figure 20).

Figure 20: Standpipe, Bell, and Overflow

In order to test the siphon I next created the overflow pipe so it stood higher than the level of the standpipe.   A ¾" x 18" threaded PVC riser was screwed into the ¾" bulkhead, and 6" was cut off. At the top end of the riser (no longer threaded), a ¾" female adapter x slip was glued onto the top, where the Botanicare bulkhead screen tub outlet was screwed in. This can be seen in Figure 21, when I tested the bell siphon.

Figure 21: Siphon Testing

To test the siphon, I filled the bed with water to the top of the stand pipe (see Figure 21), and then put the bell over the top (not pictured). I continued to fill water until it started to drain. I did not have the elbows installed yet, and the siphon failed to activate. To make it work, I had to first screw in a 1" PVC male x slip fitting into the bottom of the bulkhead fitting with the 1" stand pipe attached. Then, I glued a 1" piece of PVC cut to a 3" length to the slip opening, and dry fit an elbow, as pictured in Figure 22. After adding the 90° turn, the siphon worked.

This process was repeated for the other three growbeds, with an additional Botanicare bulkhead ½" tub outlet added to the north ends of all beds with a plastic nipple fitting on the bottom. To guard from sediment, a Bulkhead riser ¾" slip tub outlet was screwed in the top, and a Botanicare bulkhead screen tub outlet on top of that. This prevents dirty water from flowing to rafts that may be added in the future. All siphons were then tested in the same way as the first, and all worked. Everything was then glued, except the plumbing under the beds.

Next I finished piping the ¾” feeder lines that supply water from the sump tank to the growbeds. To do this, I cut the ¾” PVC to 4’ lengths and dry fit them into the ¾” male x slip adapter in the ground (pictured in Figure 15, with the addition of the fitting screwed in). On the ends of those pipes, ¾” PVC 90° angle fittings were placed on the end of each pipe facing towards the beds they feed. Next, I cut eight sections of ¾” pipe to 7” lengths. I then took four ¾” ball valves, and dry fit them on each side to the 7” sections that were just cut. Once I was satisfied with the result I glued all of the pieces together.

After the ¾” lines were completed, they were covered with dirt. I then turned to plumbing back to the fish tank. This involved tying together all of the plumbing below the siphon and overflow. The pipe size for the return plumbing, as mentioned earlier, is 2” PVC pipe. These pipes run west to east, and connect to a 3” PVC pipe that ultimately dumps the water into the fish tank. To begin, a 10’ section of 2” PVC was laid under the adjacent growbeds between the ¾” supply lines that come up out of the ground. A 2” end cap was dry fit on the west end of the pipe. Then a 2” tee with a 1” reducer bushing inside was marked on the section of 10’ PVC, while it was being held at height. This part was important, because the entire line going back to the fish tank had to be sloped so the water flows. This was checked with a level throughout the process.

After the mark was made, the pipe was cut and dry fit in place. A short 1” PVC pipe was cut to fit the bushing to the 90° elbow. To hold it in place, a sand bag with rocks on top was set under it. While that sat there, the overflow had to be piped into the

2” line. This was also done with a tee, but with a ¾” threaded bushing. This was due to the fact that I had to use ¾” polyethelene piping to fit onto the bottom of the threaded bulkhead fitting that is under the overflow pipe. PVC would not fit on the bottom end of it, so poly piping was used, and fastened with a stainless steel clamp. A poly insert male adapter was screwed into the PVC bushing, and poly piping was attached to that, which ran up to the bottom of the bulkhead fitting. These lengths were estimated, and cut to length after being marked. The piping was then clamped at the base of the growbed, as well as at the male adapter on the 2” line. At this point all components under the growbed were glued together. The 2” PVC was then dry fit into the tee that connected the overflow, and run under the adjacent growbed. Below in Figure 22 is the completed plumbing under the first growbed.

Figure 22: Plumbing of Northwest Bed Return Line

The first growbed was the easiest to hook up due to everything being in line and straight. The other growbeds were not as easy, because all of these pipes eventually had to come together to a 3” wye and enter the fish tank. This required extra steps while hooking up the overflow fittings, and ¾” poly insert elbows had to be used, in addition to extra clamps, in order to connect that to the plumbing under the growbeds. Before the second row of beds was plumbed, all pipes were laid out to ensure that they could connect to the 3” wye. Bags of sand were placed under the entirety of the piping to ensure there was a slope all the way down to the fish tank. Once this was proven, the plumbing was hooked up for all of the beds with the 2” return lines (see Figure 23).

Figure 23: 2” Return Plumbing and ¾” Feeder Lines

Next, I then had to do the same for the other pair of beds that were in line, to ensure that it would tie in with the same slope. The two sets of 2” line were connected with a 3” Wye, with 2” reducer bushings to tie into the other pipes. The 3” pipe was then run to the edge of the fish tank and marked for cutting (see Figure 24). A 90° street sweep was added to the end of this pipe, facing towards the bottom of the fish tank.

Figure 24: 2” PVC to 3" Wye

Before water could be added and the system could be fully tested, a water filtration device was installed. Chlorine cannot be present in an aquaponic system, as it will harm the organisms inside of the system. Typically, this can be off gassed if it is only chlorine, by filling a tank up with water and letting it sit for several days. However, Austin has chloramines in the water supply, which are more difficult to remove. (Bernstien 118) Several methods for removing them were suggested by Third Coast Horticulture. I could use a Hydrologic Small Boy with KDF85 filter, that can be retrofitted to hook up to the end of my garden hose, and generate a 6 gph flowrate. Alternatively, I could use a Hydrologic Big Boy filtration system with KDF85 filter, and have it installed as a whole house water filtration unit. I decided to go with the bigger option due to the larger flowrates. I found this device online for around $374. I then paid a plumber $500 to install it. Below is the picture of the filtration system installed in my house. After that, and before water was added, the grow media was added to the growbeds. Each bed required six, 50L bags of Hydroton.

Figure 25: Chlorine Filter Installation

The last part of construction for the system itself was adding the overflow standpipe that connects the sump to the fish tanks. This pipe connects the two tanks, and as water flows into the fish tank, water is forced through this pipe, over to the sump tank so that it can be pumped back through the growbeds. I initially drilled a 3” hole with a hole saw 4” to center from the top of the tanks. Then, I placed in a 2” uniseal in each of the holes. Astroglide, a water-based lubricant, was used (as well as a lot of force) to fit the 2” pipe through the uniseals. A 2” 90° fitting was placed on the end in the fish tank, and a pipe was cut to the length such that it sat 1” from the bottom of the fish tank. The grow media was added to the growbeds, and water was added to test the flow of the system. In addition, the 1 ½” PVC that runs from the sump to the growbeds was hooked up to the pump. A 90° fitting was attached on the end of the pipe, facing upwards, and placing a 2” long section of 1 ½” PVC in it. Another 90° elbow was placed on the end of that, followed by a two 1’ pipes connected by a 45°angle fitting. Another 90° elbow was used to pipe the 1 ½” line down to the pump. The pump, a Mondi 1500 gph pump, required a 1 ¼” pipe. This was remedied by adding a reducing coupling 1 ½” x 1 ¼”, to the pipes, and tying in the pump with a 1 ¼” female x slip fitting (see Figure 26).

Figure 26: Pump Connection and Water Flow Testing

The initial water test ensured that all siphons worked correctly when the pump was turned on, as well as the overflow standpipe that connected the fish tank and sump tank. At first, everything worked well; the siphons all fired on cue, and shut off when the growbeds were drained empty. However, the overflow standpipe could not handle the water coming in when all four siphons were activated. The fish tank overflowed under this condition.

To remedy this problem, I used a larger diameter pipe. I extracted the pipes, and drilled a 5” hole in the tanks, concentric with the existing holes. This was very difficult to accomplish due to the fact that there was nothing for the hole saw pilot drill to grab onto. I used a piece of scrap wood wedged between the fish tanks in order to ensure that the holes were accurate (see Figure 27).

Figure 27: Creating Larger Holes for Overflow

This process was repeated for both reservoirs, and was carefully done to ensure that the holes were level with each other, and in line. A 4” uniseal was placed inside each of the 5” holes, and Astroglide and force were used to force the 4” PVC pipe into the openings. The stand pipe was finished out the same as before, with the only change being that I used a 4” wye, rather than a 90-degree fitting, to prevent any siphoning action from occurring if the water ever fully covered the opening in the sump tank. This was then tested in the same fashion as before, by adding water to the fish and sump tanks (see Figure 28).

Figure 28: Second Water Test

At this point all of the plumbing worked; however, there were still a few issues to address. First, I was concerned with the murky red color of the water as seen in Figure 28. I devised a plan to filter this out, by placing towels under the ¾" feeder lines in the growbeds (see Figure 29). This indeed removed all of the red coloration from the water, however, the detergent residue that was still on the towels leeched into my system (see Figure 28). All of the water had to be drained, and the media was rinsed furiously to get all of the detergent out. I recommend rinsing the grow media before placing it into the growbeds to prevent this mistake.

Figure 29: Towel Filtering the Water

The last issue I had to deal with was the pollen and leaves from the tree that kept inundating my grow beds. I had to spend twenty to forty minutes daily extracting debris from the grow bed area. I quickly had to find a solution to fix this issue, for I was afraid that any added unknowns would alter the chemistry of the system. I constructed a PVC structure around the footprint of the growbeds to support a cover to prevent debris from entering the system. This structure can also support a shadecloth hung over the top during the hottest months in Texas, as well as a complete cover to create a greenhouse effect during the winter. Below, in Figure 30, is a sketch of the design.

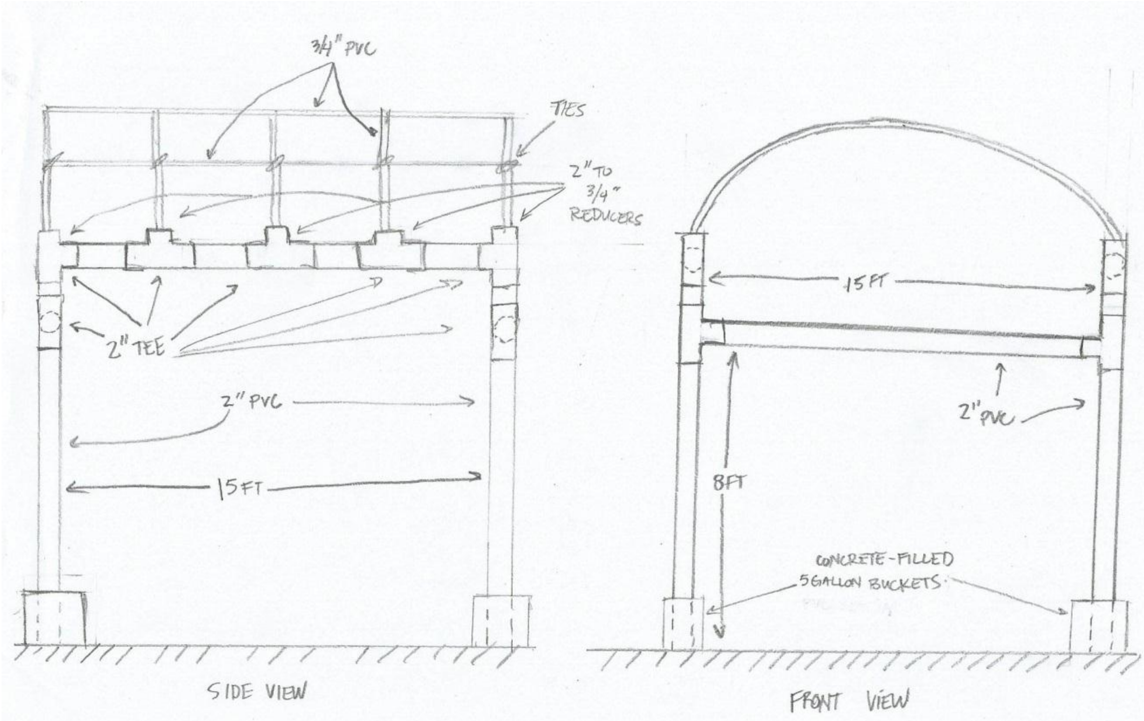

Figure 30: Design of PVC Structure

The design of the structure is simple. Concrete poured into 5 gallon buckets holds 2" PVC risers in place, with a maximum height of 8'. At the top of the risers, 2" tees connect the adjacent sides. On the west and east sides of the structure, 2" tees are fitted with bushings that reduce down to ¾" which are connected by ¾" PVC across, forming an arch. In total, there are five arches that span across the top of the structure, where the shadecloth and/or plastic will sit. An additional ¾" PVC pipe runs across the arches in three sections, connected by PVC cross connectors. The entire structure is 15' x 15'.

To complete this, I had already exhausted all of the help I could get, and had to hire someone. I became the helper during this project. The structure itself turned out well, with the only difference being that diagonal supports were added on four of the corners, and there was four additional concrete-filled 5 gallon buckets added to the center of the spans. PVC is not as rigid as I thought.

Below are pictures of the completed project (Figure 31 and Figure 32). At this point, plants were added, and cycling was begun, which will be discussed in the next chapter.

Figure 31: Completed System 1

Figure 32: Completed System 2

Chapter 5

<u>Cycling the System</u>

Cycling the aquaponics system refers to "establishing a biofilter where the nitrogen cycle can take place within your system." (Bernstein 183) There are two ways to begin this process, with fish and without them. I chose the latter, due to the fact that I was apprehensive about trying to manage this new process while trying to keep fish alive. Also, when cycling without fish, "you can elevate the ammonia concentration to a much higher level than would be safe for the fish… and [can] cycle your system in much less time." (Bernstien 189) To begin this cycling process, one must add liquid ammonia(NH_3) to the system. I bought some cheap janitor's ammonia to do this. Once ammonia is added, nitrosomonas bacteria will be attracted to your system, which is the first addition to the biofilter, and is a naturally occurring nitrifying bacteria. This process takes place due to ammonia is changed into ammonium (NH_{4+}). "Fish excrete ammonia (NH_3) through their gills as a byproduct of their respiration process. In addition, ammonia (NH_3) continually changes to ammonium (NH_{4+}) and vice versa, with the relative concentrations of each depending on water's temperature and pH." (Bernstien 187-188) As temperature and pH rise, there is a higher percentage of ammonia in the system. Nitrosomonas bacteria convert ammonium, into nitrite (NO_{2-}). Both ammonia and nitrite are toxic to the fish, which is another positive of cycling without fish. After nitrites are present in the aquaponic system, another form of bacteria naturally populate and colonize on the grow media of the system, nitrospira. Nitrospira bacteria convert nitrites, into nitrates (NO_{3-}), which are “generally harmless to the fish and important food for your plants.” (Bernstien184)

Materials used during the cycling process included janitors ammonia, potassium carbonate (K_2CO_3), and calcium carbonate (Ca_2CO_3). In addition to using these chemicals, a 5 gallon bucket full of cycled water was added intermittently from a mature aquaponic system, to speed up the process. To test the nutrient levels and pH, an API Freshwater Master Test Kit was used. These tests included ammonia, nitrite, nitrate, and pH levels. Directions were followed on the kit as printed in the instructions.

In order to correctly cycle the system, I filled the sump and the fish tank with water. I also let the pump run for over an hour in order to double check the plumbing and flow of the system. Next, I added two capfuls of the janitor’s ammonia and then tested the ammonia levels. I repeated this process every thirty minutes until the test read 4.0 ppm. The target pH level of the water was close to 8.0, per the information obtained at Third Coast Horticulture. I tested the pH levels, and they were right at 7.0. To raise them, I added 1 tbsn of each of the potassium carbonate (K_2CO_3), and calcium carbonate (Ca_2CO_3). I waited an hour, and tested the levels again. The pH was at 7.6, which is in the acceptable range.

Below in Table 2 are the data I collected during the cycling process. Each day I noted the starting pH, what was added, the ending pH, ammonia levels, nitrite levels and nitrate levels. The cycling process is complete when the nitrites and ammonia levels drop to zero, while there is a measurable amount of nitrate. This can be seen below.

Day	Ammonia (ppm)	Nitrite (ppm)	Nitrate (ppm)	pH Before Additions	pH After Additions	Additives
1	1	0	0	7	7.6	1 cap of ammonia, 2 tbspn K2CO3 + Ca2CO3
2	4	0	0	7.2	8.5	3 caps of ammonia, 1 x 5 gallon bucket of AP water, 1 tbspn K2CO3 + Ca2CO3
3	4	0	0	7.2	8	1/2 tbspn K2CO3 + Ca2CO3
4	4	0	0	7	8.2	1 tbspn K2CO3 + Ca2CO3
5	4	0	0	7	8.3	1 tbspn K2CO3 + Ca2CO3
6	4	1	0	7	8.2	1 tbspn K2CO3 + Ca2CO3
7	4	1	0	7	8.2	1 tbspn K2CO3 + Ca2CO3
8	4	2	0	6.5	8	5 Gallons of cycled water, 1.5 tbspn of K + Ca2CO3
9	8	3	10	6.5	6.5	Rain, 1.5 tbspn K2CO3 + Ca2CO3
10	4	4	10	6	7.5	Rain, 1.5 tbspn K2CO3 + Ca2CO3
11	2	5	10	6.8	7.6	Water exchange due to 3.5" rainfall, 1 cap ammonia, tbspn of K2CO3 + Ca2CO3
12	0	4	40	6.3	7.6	1.5 tbspn K2CO3 + Ca2CO3
13	0	2	40	6.5	7.6	1 tbspn K2CO3 + Ca2CO3
14	0	0	40	6.5	7.4	1 tbspn K2CO3 + Ca2CO3

Table 2: Cycling Data

5.1 Adding Fish (Post Cycling)

Fourteen days after I started, the ammonia, and nitrites reached 0 ppm. The pH levels seemed to drop throughout this whole process, which caused the addition of the calcium carbonate and potassium carbonate. At this point cycling was complete. Before

I added fish, I added a can of worms with their casings, dividing the can evenly between the four growbeds. Next, thirty fish were placed in the 180 gallon tank, while daily monitoring the ammonia, nitrate and nitrite levels in order to ensure a spike did not occur. Nothing happened after 2 hours of testing. At this point, the prototype was fully functioning.

The very next day, the pump failed completely. I returned the Mondi pump and bought a different brand of pump called the EcoPlus 1500 Elite Submersible Pump. The problem with this, however, was that the pump connection diameter was 1” rather than 1 ¼”. So I had to convert the pump connection. I did this by cutting the old pump connection in half with a saw, then buying a 1 ¼” reducer coupling. I glued in a 1 ¼” x 1” reducer coupling, and connected a 1” pipe down to the pump. The pump connection was connected with a 1” female PVC x hub, and the pipe between the coupler and the pump was dry fit, in case I need to replace the pump in the future.

I also noticed that some fish were jumping out of the water. To fix this, I used some ¾” Styrofoam wall insulation cut to the size of the top of the fish and sump tanks using a utility knife. This not only blocks the light to reduce the amount of sunlight that reaches the tanks, which thereby kills algae growth, but also prevents the fish from jumping out of the tank. Algae growing in a system, they can deplete the dissolved oxygen overnight. (Bernstien 122)

Three days after I added fish, I noticed that the ammonia, nitrite, and nitrate levels all were still at zero. The twenty-eight fish (two jumped out) were not producing enough waste in order for any levels to be detected. I added forty-seven more tilapia to the tanks, hoping this would change. Four hours after adding the fish and feeding them, my nitrate levels reached 10 ppm, my nitrite levels were 0 ppm, and my ammonia levels rose to .25 ppm.

Since then the system has stabilized. Liquid kelp has been added twice, in order to aid in the development of a mineralization zone at the bottom of the growbeds. My nitrate levels seem to hover around 40 ppm, with the ammonia at 0 ppm and the nitrate at 0 ppm. My plants have since experienced great growth. Below in Figure 33 is a picture of plant growth seven weeks after cycling began.


Figure 33: Plant Growth

Chapter 6

Curriculum Implications

The problem with aquaponics being used in the classroom is that there are so many directions in which one can go with designing in the curriculum, and so many different facets of core subjects to focus on that it at first seemed overwhelming. The content itself is a challenge that must be addressed if this is to truly integrate other subjects into an engineering design project, so that the mathematics and science content is mandatory to complete the project. To remedy this and make it relevant for a classroom, the mathematics and science will be built into the project as milestones, deliverables, research, and constraints.

Another important issue with designing something that could work in a classroom is cost. My aquaponics system was very expensive compared to the amount of money any department within a school might get on a yearly basis. My design would definitely have to be scaled down such that a typical class can afford to do a project like this. In 2002, the University of Arkansas via the AgriScience Education Project put together an aquaponics program called "Aquaponics in the Classroom" where a low cost aquaponics unit was given to teachers ranging from K-12 in order to teach mathematics and science content to their students. (Wardlow 1) The units themselves cost $350, and curriculum was provided to the teachers in order to help them teach various content. The mathematics and science content is spread throughout with activities such as " 'Determining the Water Cycle Rate' and 'Determining Feed Conversion Rate' (mathematics) … and ‘The Nitrogen Cycle’ (chemistry); ‘Evaluating Pumping Efficiency and Power Factor’ (physics).” (Wardlow 3) I do think $350 is plenty of money to set up a project for various groups within a class. However, if there are multiple groups, this may be a problem which will require additional funding either via local grants such as the Lowe’s Toolbox for Education Grant, Title 1 money (if available), or from the principal’s discretionary fund (if applicable). Having an aquaponic system project in a high school classroom will be expensive to operate. The end of this chapter will address how to find funding.

Aquaponics is a full time job. There are no breaks. Every day the fish must be fed, pH must be checked, and the plants must be tended to. Other issues such as nitrite and ammonia spikes may have to be dealt with intermittently as these levels can be tested weekly once the chemistry of the system becomes more stable. Pests can also take their toll on the plants within a system. The point here is that some teacher or group of teachers will have to take the responsibility of letting students in on the weekends, to tend to their projects. This time commitment is large, and the right person will have to be found to complete a project like this. Student interest must be cultivated such that they express the interest to commit the thirty minutes a day it takes to take care of their project. Since the students will be in groups, this can be managed by splitting up the time and work required to do this. However, dedication on the students’ part as well the teachers’ can make this project successful.

The final issue regarding implementing a project like this in the classroom is teacher experience and the connectedness to a learning community that can bolster student learning. Without the help of the people at Third Coast Horticulture, I could not have completed my system. Actually seeing functional aquaponics systems, as well as collaborating with people who were in the store shopping, proved valuable in my learning experience. I also would not feel comfortable doing a project like this, unless I had done it before. I think building a small system before implementing the curriculum would prove fruitful for the teacher, so there is some base knowledge of designs, how each component works, how to water quality test, and how to deal with issues that may arise. You can read about this all day in many texts, but as with many things, experience is vital for this to succeed.

As mentioned before, there are many directions this project can go. My vision is for it to be a capstone project for a senior course, either in an Environmental Systems classroom, or a Scientific Research and Design classroom (capstone engineering design course). Environmental Systems is a course that deals with life science and how it connects to the real world. Many of the issues laid out in the introduction of this paper, are brought up and learned about in detail in Environmental Systems. However, there are more constraints as far as curriculum placed in core classes, which is why an engineering course would allow more freedom to explore cross-curricular subjects, while still developing engineering habits of mind.

Scientific Research and Design is a Career and Technology Education course that is typically designed for seniors as well. It has very broad standards and generally is not attached to specific core content that may hinder the ability for a teacher to have a project like this. Although academic standards are good in the sense that they can hold teachers accountable in what they teach and help them develop instructional materials to do so, they can also inhibit the ability of subjects to become more connected through real life problems, such as aquaponics. This curriculum outline will be much more difficult to complete in a core class due to the stringent menu of concepts that must be covered. Teachers will need flexibility and full autonomy in their classrooms in order to be successful.

Before the teacher begins a project like this, he or she will need to collect basic materials that every system will require. This may be determined geographically. For example with regard to water filtration, teachers in Austin, Texas will need to purchase a filter to expel the chloramines in the water. In the Appendix, on page 88 is a list of basic materials a teacher might need in order to get started. Of course, depending on the size of the class, the quantities may be different, but this bill of materials assumes a senior level class of 15 students. The colors within the table are for different aspects of the project. The blue color represents things needed for the maintenance of the aquaponics systems. I did not include fish feed, for that should be accounted for in the students' budget when planning their own system. The yellow items are needed if constructing out of wood. If my students went this route, I would charge them by the square foot of duraskrim, and by the linear foot for the tapes, so they can factor this into their budget. The white items are miscellaneous items that will be used frequently throughout the project. A class set of books is a must. The red items represent power tools and accessories that were used in the construction of my system. Of course, basic tools such as utility knifes and measuring tapes will need be needed, based on the design and requirements of the students. Based on the teacher's experience with tools, there may be a personal preference as to which tool to use for what.

To start a project, from my experience, some kind of hook is needed to get kids interested in the task at hand. This hook should provide guidelines to the purpose of the project, and keep the end in mind. In other words, this problem statement, along with the entry document, should be referred to frequently so that students can see why they are doing and learning the things in a project. This hook lays out the problem, and shows that there is some kind of need that makes the project relevant to the students' lives. In this case the problem statement will come in the form of a challenge:

Problem Statement for Students:

> Environmental degradation and rising food prices can result from modern agribusiness practices and scarce resources. Design, build, test, maintain and troubleshoot a backyard aquaponic system in order to grow food more sustainably, and sell the food for a profit.

This challenge will be given after information presented in this report's introduction is presented to the class in some form or fashion. Context is extremely important, so that the information can be discussed and situated with the group of students. This, coupled with the design brief, found on page 89, will create buy-in for the students as to why constructing an aquaponics system is relevant.

In an engineering course, the flow of a project is easily facilitated by following an engineering design process. Since one of the main components of a high school engineering course is design, an engineering design process can be followed, such that students will become more and more familiar with it as they track through high school. In my case, I chose the UTeach*Engineering* Design process, which was created for the course *Engineer Your World*, as the basis for my project's flow. This can be seen in Figure 34, below.

A word about the design process: there is no set design process to use. They are different across the board; different universities use different design processes, as do companies. The idea is that it is a progression of logic that is iterative, such that whatever is being designed can be redesigned and improved.

The last assumption about this curriculum outline is block scheduling. But, as with every curriculum, it is meant to be changed, altered, and fit to best serve the teacher and provides a basic outline of the flow of the project.

6.1 Modernism and Post-Modernism

The curriculum, with the aid of the design process, is meant to have elements of both post-modernism and modernism embedded within it. Modernism is a mode of curriculum development that is strongly influenced by Ralph W. Tyler, where the pre-determined end is the goal of instruction, which is driven by the selection of standards. The "pattern [in school curricula] is the same: pre-set goals, selection and direction of experiences, evaluation." (Doll 54) This curriculum does in fact have a pre-determined end, in that it seeks to teach multiple subjects in science and engineering under the context of an aquaponics challenge. It also provides the means to teach these goals by laying out the direction of the experiences within it. In fact, it would be difficult to justify doing a project without being able to justify the standards that will be covered in any classroom today. In that sense, this project follows a modern model of curricula.

However, the curriculum itself is meant to be prescribed, but not necessarily enacted exactly as it is written because of the difference in individual classrooms, teachers, and students. As mentioned above, it is meant to be adapted and altered to fit the end user. In a sense the design process is the same way. Although its trajectory as one moves through it is linear, it is by definition recursive. Any part of the design process can be repeated, depending on the project that is being worked on and the results obtained. This is a post-modern trait.

In a post-modern context, "Curriculum materials can be organized to encourage reflection if they are approached iteratively and recursively, not linearly." (Doll 102) This curriculum can also be iterative and recursive, depending on the mode of teaching the teacher employs. According to Doll, recursion is a way for "developing competence – the ability to organize, combine, inquire, [and] use something heuristically." (Doll 178) For example, if students are particularly interested in the physics of how bell siphons work, more time can be spent on it within the curriculum, or if inquiry spurs interest later on in the project, it can be revisited in order to better understand it. For this to occur, autonomy is needed, thus furthering the cause for this curriculum to be executed in an engineering course.

Although a goal is to allow for freedom of student inquiry, the majority of the curriculum is prescribed and focuses on learning multiple subjects of engineering, mathematics, and science content. The design process and the design of the curriculum are the same in the sense that they do have an outline to follow. It the manner in which it is enacted that will determine the modern or post-modern nature of each.

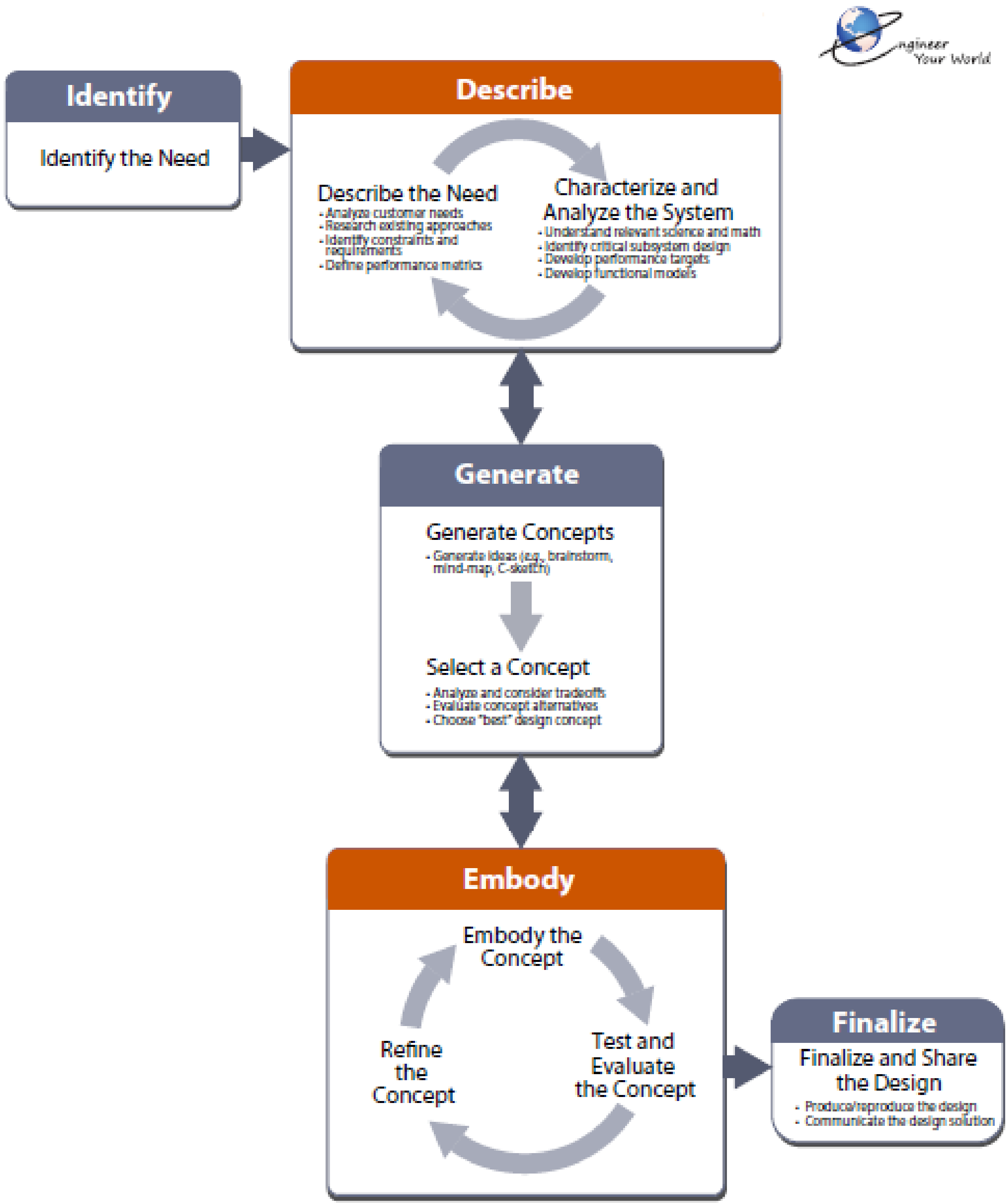

Figure 34: Engineering Design Process

6.2 Project Outline: Design, Build, and Maintain an Aquaponic System: An Engineering Approach

An authentic method used to facilitate a project in an engineering course is to follow the design process. This outline does that and is arranged in blocks. Given the large time commitment this project requires, I recommend beginning this project towards the middle of the first semester, in October. This will give some time to learn about the background of the project, and refresh the memory of the class about what design is, and the like. It should also be timed, based on this outline, to have the system constructed towards the end of January into February, which is a good time to start seedlings so the students can see plant growth.

IDENTIFY: DEFINE PROBLEM

Block 1: The students are given the book “Aquaponic Gardening” Book, and will read chapter 2 in class. Students write facts they thought were interesting, and share out. As students share out, teacher writes down things students share while the students take notes in their engineering notebooks. This is so that the information can be reviewed during the next class period.

Block 2: Begin class with a brief discussion of the previous block’s information, showing students the summary that the teacher wrote as discussion ensued. Handout the Design Brief document (found in the Appendix on page 91), which is the entry document that will spur student questions. Have students read this document, then have a discussion about what students know, and what they need to know (template found in Appendix on page 92) in order to successfully design this system. The teacher should write these things down as students discuss them in order to present to the class what was found. Students should bring up, how they are going to calculate the yearly cost, or something of the like based on the constraints in the design brief. In the "need to knows", the teacher will record the students' questions about feed conversion ratio, power, voltage, amperage, and feed rates. Afterwards, split the students into groups, and have the groups discuss roles and responsibilities. Have them sign and draft a contract with each other, to hold each other accountable for tasks and workloads. Make copies and have the students put both the design brief, as well as "knows" and "need to knows" in their engineering notebook so that the information is documented.

Block 3: Have the students read chapters 1 and 3 in "Aquaponic Gardening". This can be done in class out loud, or silently. Conduct a discussion about the information in it, and have the students record in their engineering notebooks why this is important, as well as how it relates to why a family would want something like this (to connect to the design brief). This could be done as a homework assignment.

Block 4: Utilizing the internet as well as (Bernstein) have students organize different types of aquaponic systems (template found in Appendix, pages 93-95). Using the template, have the students in each group break down the pros and cons of each system as well as relate it to the nitrogen cycle. In a worksheet, students fill in the names of different types of systems and characteristics of each. This exposes the students to the different types of systems and provides a larger knowledge base so their designs are more robust.

DESCRIBE: DESCRIBE THE NEED

Block 5: Research: Student groups go online and/or use (Bernstein) to find a type of media based system configuration, since this is one of the constraints outlined in the design brief. Students choose one media based system, and go online and find a working system. Using the "Existing System Research" template, found in the Appendix on pages 96-97, have the students detail information about a system that is functioning. When finished, the students should document their findings in their engineering notebooks. Again, the purpose of this assignment is to research what is available in terms of media based systems, in order to aid them in making design decisions of their own.

Block 6: Deliverable: Research presentations: Students choose one type of system (media based system configuration), and present information detailing what they learned from each different type of system, and the design they found on the internet. Other students in the class take notes on this presentation in their engineering notebooks, so they may gain more knowledge on what specifically is out there. This block will generate more ideas since students will focus on different types of configurations and ways to accomplish the task at hand. Ultimately it will spur more ideas for their own design.

CHARACTERIZING THE SYSTEM:

Block 7: Bell siphon anatomy: Student learn about bell siphons and how they work. This may or may not be integrated into their design, as they may choose to use a timer.

However, bell siphons are an effective way to make the plumbing work in aquaponics, and much can be learned about the different ways to build them that would be beneficial for the students to use in their design. A YouTube video that describes how they work can be found at https://www.youtube.com/watch?v=gFokOynqOqQ. Everything should be documented in the engineering notebook. When the students finish, the teacher should check notebooks and give feedback on what has been documented prior to this assignment, as well as for this assignment in order to check for understanding and ensure the students are getting multiple ideas to draw from.

Block 8: FIELD TRIP: Students can go to an aquaponic store and/or someone's backyard system to see a working product. This way students can see what works, and the experience will aid in generating concepts. Notes can be taken on the "Existing System Research" template found in Appendix on pages 96-97.

Block 9: The teacher works with students on developing functional models. Black Box modeling should be completed first, then functional modeling that details the life of the product they are designing. These should be documented in their engineering notebooks, and the level of depth is based on how familiar students are with this type of modeling, as well as the teacher's comfort level with functional modeling. This block gets students to think about these systems in a systems thinking type of way. How will the system be used? What are the inputs? What are the outputs? This will help when generating concepts if students think about the system in these ways.

GENERATE CONCEPTS

Block 10: Students conduct a brainstorming session, by listing as many aquaponics systems concepts as possible in their engineering notebooks in groups. Students then transfer their ideas to yellow sticky notes. Next, they stick them on the wall. As students place their ideas on the wall, the teacher will group them into categories. Categories should emerge naturally with related ideas pertaining to their system. These should be documented in students' engineering notebooks so they can refer back to ideas that emerged as a class.

Blocks 11-12: Concept Selection: Students record a justification as to what design they want to go with, and explain how their concept satisfies constraints outlined in project launch. Students also justify the grow media they chose, the configuration of the system, the growbed to fish tank ratio, and how the water flow in the system will be handled and controlled. Also, they must document the inspiration for their system, if it came from the field trip, or a design they found online.

EMBODY

Blocks 13-16: Structural Analysis: Students will calculate loads on their stand (if present) using statics principles to ensure it can handle the load of their system. It would be best to introduce the concepts of statics for a day or two, and then have them apply the concepts to their designs. This fulfills the constraint of ensuring that the design is structurally sound, for students will calculate a factor of safety for their stands. Example calculations for my beds are given below.

To begin the static calculations of the stands, first draw a free body diagram to analyze the forces on the structure. Figure 35 shows the free body diagram of the structure. In order to calculate the loads on the legs, the load itself distributed across the four joists must be calculated first because they distribute the load to the two end beams that run perpendicular, which ultimately distributes the load to the legs.

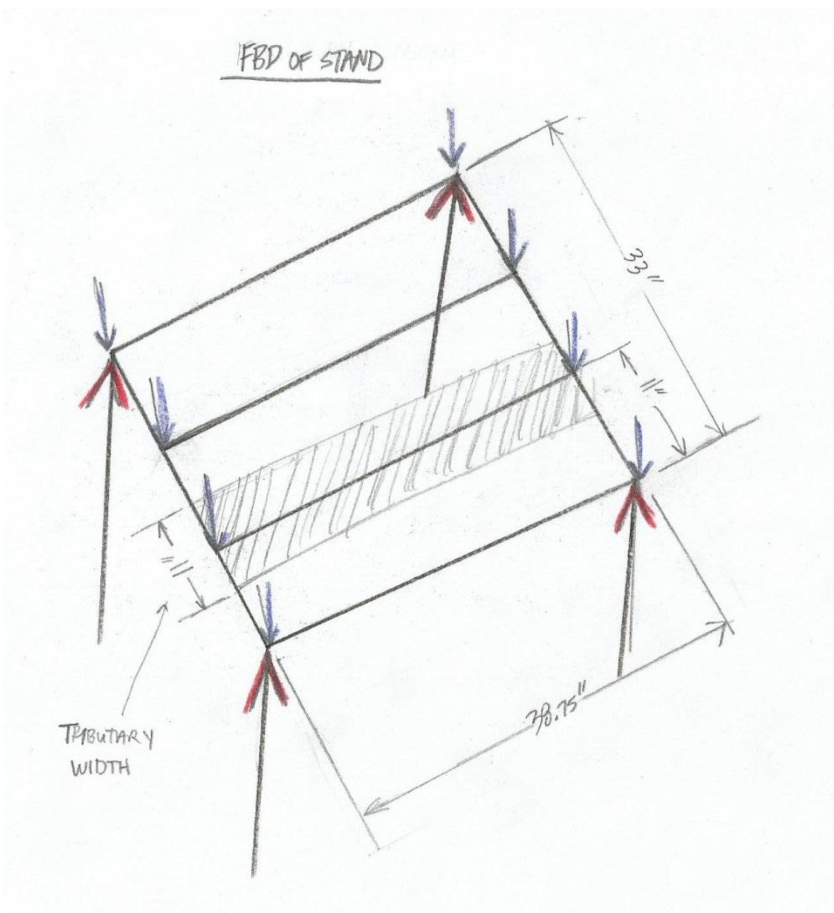

Figure 35: Structural Analysis of Stand

First, the load must be calculated for the growbed itself. Six bags of Hydroton weighing 50 lbs went into each growbed. Since the maximum water height in the beds is 9", the volume of water is 12 ft^3 which translates to 89.76 gallons. Each gallon of water weighs 8.34 lbs, which brings the maximum load due to the water to 748.60 lbs. I estimated that the plants, as well as the growbed itself weigh about 35 lbs. In total, this brings the load of each growbed to 1083.6 lbs, or 1083.6 lbs / (3.229 ft * 2.75 ft) = 122.03 psf. With the load distributed evenly, the tributary area can be utilized in order to calculate the linear load rate distributed across each of the four joists. Since the total load is 122.03 psf, the uniform load that is distributed to the joists is this load multiplied by the tributary width, which comes out to be 111.86 plf.

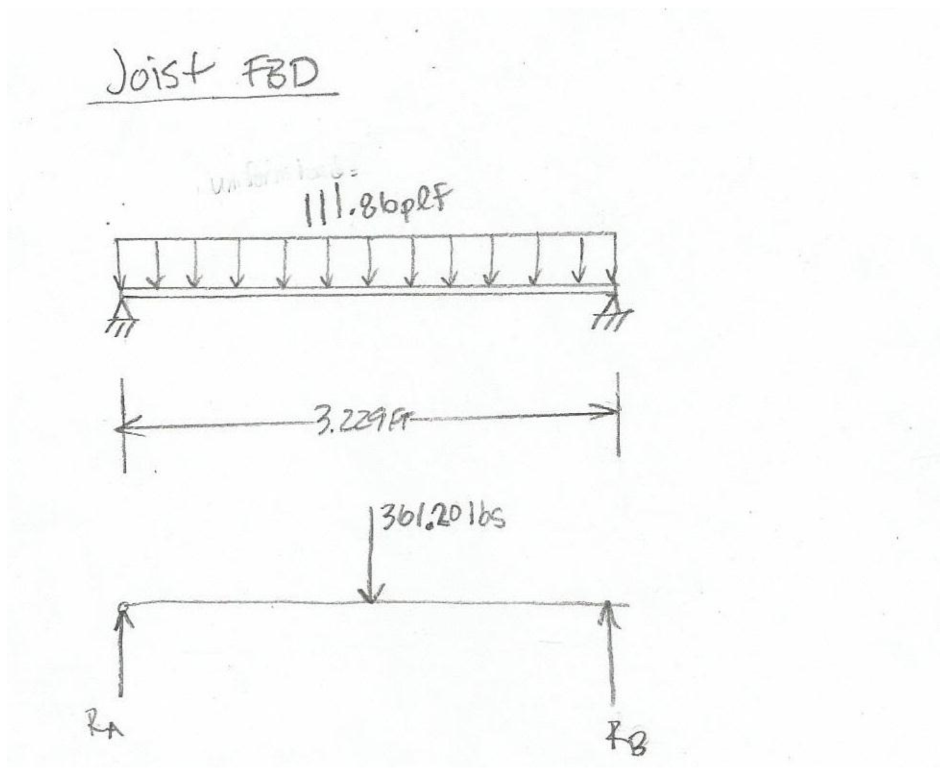

Figure 36: Joist FBD

Since the load is uniformly distributed, the effective load can be redrawn on the FBD at the center of the joist, if the length of the joist is multiplied by the uniform load. This comes to 361.20 lbs. The reaction forces at the ends are distributed evenly and are 180.6 lbs each.

On the end joists, since the tributary area is half of that of the inner joists, this load is halved, and is 90.3 lbs on the ends. The FBD of the two beams that distribute the load down to the legs is pictured in Figure 37.

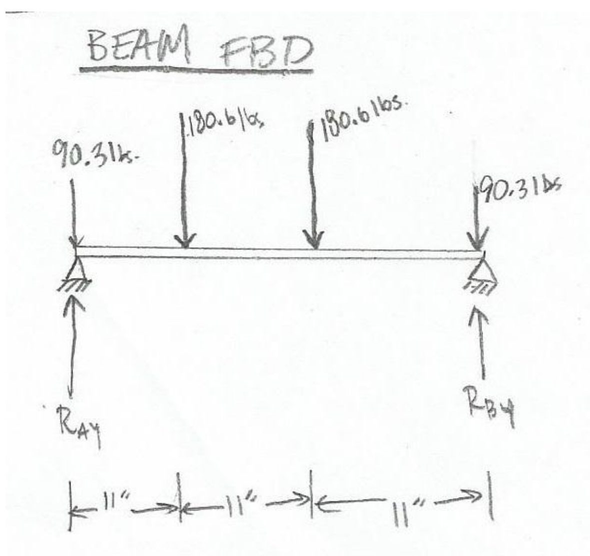

Figure 37: Beam FBD

Since the distance is equal between all of the forces, the reaction forces at each of the legs are just the summation of the forces divided by two. This comes to 270.9 lbs at each of the legs. Of course these assumptions will have to be addressed in the class, and practice will be needed before students can make these assumptions with their static calculations.

To calculate the factor of safety, first the maximum stress must be calculated for the design. Stress is calculated by as the load and divided by the cross-sectional area of the material used. In this design, each of the tubes is a 1 ¼" galvanized steel tube. From http://www.engineeringtoolbox.com/ansi-steel-pipes-d_305.html, galvanized steel pipe inner and outer diameters can be looked up. The cross-sectional area of my pipe is .669 in^2. This makes the stress of the pipe 404.9 psi. The maximum yield stress, of this galvanized pipe, taken from http://www.atc-mechanical.com/tube-pipe-101/specifications-galvanized-structural-steel-tube-pipe/, is 30,000 psi. This gives a factor of safety of 74.09.

Blocks 17 - 18: Students must now create a list of parts to build the system, ensuring that the materials they choose can withstand the load of the growbeds. This should be placed in an Excel spreadsheet, including prices and sources, proving they are below budget. I recommend leaving at least $50 dollars for potential mistakes, and $30 for fish food. Students should be able to scale down for parts to total around $220. Materials should be local, so that the student or teacher can drive to get them, as well as to avoid shipping costs.

Blocks 18-19: Plant metrics: Information about the plants that are chosen should be recorded so that an inferential projection can be made about the amount of crops they will be able to produce in a given year. Things the students should include are: What plant do they choose? How much per pound does it sell for locally? How long does it take to fully mature? How far apart must they be spaced to be successful? When in the year can it be grown?

Blocks 20-21: The students and teacher purchase parts. This can be done either online, or as a class field trip to a local hydroponic or aquaponic store. This could also take time, due to the fact that every school district has policies and procedures to sift through in order to purchase materials. Unless everything is local, this too could cause an issue if parts are being mailed. Depending on the district, it is recommended to constrain the students to buy materials locally (if possible). Also, at this point all of the materials, as well as the plants the students will use should be ready to buy. The large majority of purchases should be made at this point.

Blocks 22-29: Students under teacher supervision construct the systems. Safety training should be completed on all power tools before students begin working. The construction should be driven from the design that is generated and documented in their engineering notebooks.

TEST AND EVALUATE

After the seeds are bought and the system is built, students should start the seeds so that they can be planted once cycling begins. Cycling will take anywhere between two weeks and six weeks.

Blocks 30-31: After the system is built, cycling begins. At this point, plants should be introduced to the system. Nitrate, nitrite, ammonia, pH, and temperature should all be tested and recorded. All data should be in Excel, for the final report. Also, a chemistry lesson the cycling process could be introduced. If chemistry is considered in more detail, it is also a good time to throw in a balancing equations workshop so the students can practice those skills and relate them to the nitrogen cycle present in the system.

Block 32-33: Calculating pump cost: Since the cycling will take a considerable amount of time, other tests can be run, such as calculating the pump cost. First the physics concepts are reviewed relating to power, current and voltage. A worksheet may be given to have students practice the skills. In the second block, the students carefully measure the current drawn by their pump using an ammeter. Assuming a 120V power supply, use the measured current in amperes to calculate power, and divide by 1000 to convert to kilowatts. Multiply this by the number of hours in a year, and find the price per kilowatt-hour of electricity. This will be factored into the final cost calculations.

Once nitrites and ammonia levels reach 0 ppm, and there are nitrates present (the teacher should confirm levels), students can add fish. Either goldfish or tilapia are a good choice; tilapia can be eaten and sold for more money, while goldfish are cheaper are more robust as a species.

Blocks 34 – 44: Feed conversion Ratio: Once the students add fish they should be weighed so the students can find the initial weight of the fish biomass entering the system. This can be done by taking a 5 gallon bucket, weighing it with water in, then placing the fish inside the bucket and weighing again. After the beginning biomass is recorded, students must weigh and record the amount of feed are using. This should be done over a length of time of about 2-4 weeks. The feed conversion ratio (FCR) can be calculated as:

FCR = feed give (lbs)/ biomass gained (lbs)

Background information supporting this, as well as a worksheet of this topic can be found at: http://calaged.csuchico.edu/resourcefiles/curriculum/advcluster/3158.txt. Use FCR to determine the amount of fish biomass produced each year by projecting how much feed they will use in a year. This gives the total fish biomass that can be produced. This can be used in relation to tilapia or goldfish, and is a general concept that applies to other animals in agriculture.

After a crop has matured, students can make inferences about how long it will take to pay back the initial $300 investment. This should be included in their report along with their design process, construction process, structural analysis, and power cost calculations, as well as plant metric information and projections.

This could very easily be a year-long endeavor for a student. Although many of the materials have yet to be created, the idea of integrating multiple subjects together is embedded in this project, with the ability to add many more subjects, such as biology and chemistry. However, since I have yet to prototype this project in the classroom, the details of integrating other subjects are vague.

For funding purposes, it also makes sense to complete this project in a CATE setting. As an engineering teacher, I receive more money than the entire mathematics department at my school. For a project like this though, which will require upwards of $4,000 for a classroom, I would need to find more money in addition to the funds I get from CATE. To secure funding I recommend writing grants during the year prior to the one in which this project will take place. A good resource for finding grant money for this project, in Texas, is http://texas.grantwatch.com/cat/10/environment+grants.html. This resource of course is tailored towards Texas schools; however, there are multiple search engines for grants that may be available in other areas.

Additionally, most districts have personnel that deal exclusively with grant writing. If seeking grants seems overwhelming, contact the human resources department at your district to utilize this resource. This of course, may vary depending on the size of the district. However in mine, specifically in the CATE department, there are people who help with finding and writing grants.

Chapter 7

Application to Practice

While completing the Master's of Arts in STEM Education – Engineering program (MASEE) at The University of Texas at Austin, I completed a rigorous mix of engineering and education courses designed to prepare me for teaching an engineering course that the University had been developing titled *Engineer Your World*. The course itself contains several design challenge projects that introduce students to a variety of engineering disciplines and concepts, which are intended to build engineering habits of mind, while giving exposure to various fields within the engineering profession. The projects themselves range from designing a pinhole camera to reverse engineering and redesigning various objects such as a hand-powered flashlight. Each project is engaging for a variety of student demographics, and has relevance due to the focus on approachable technology.

Students within the MASEE cohort were allowed to choose a master's project from several engineering groups at The University of Texas, who are working on various graduate level research topics within different fields of engineering. We were also allowed to choose from various education professors and work on topics that were of interest to those faculty. Some of us, however, chose to go a different route in their research. I was one of them. My experience in teaching has primarily been in mathematics, with two years of teaching Algebra 1, both in a project based setting and in a traditional setting, Precalculus, and a freshman level Project Lead the Way course titled Introduction to Engineering Design. These experiences influenced my choice of this research project for completing my degree. While learning about engineering design and the educational theory I was not exposed to in post-secondary studies, I realized that I too wanted to contribute to the array of design challenges offered and developed at the university. This report, describes the realization of a goal that piqued my interest several years ago.

Aquaponics is and has been something that I have wanted to do, but have always been too busy with life to set aside the amount of time needed to actually do it. It is the fusion of hydroponic gardening – growing plants without soil, and aquaculture – raising fish for food. Given all of the news one hears about the food supply, and what actually goes into our foods and the production of it, I have wanted to do something about it for myself and my family for some time. And with the newest addition to our family, it is something that has come to fruition.

It took the guidance and learning of the MASEE program for me to actually design and build a system of my own. The engineering design process is wonderful to use as a way to solve real life problems. In fact I often ask my engineering students at the end of the year how it can apply to everyday life. Some see its utility outside of the classroom, as I have. As I started to gather my thoughts of my own system, and through the reading I was exposed to in the MASEE program, I began to realize that this project would be rich to explore in a school setting. It combines several concepts at the foundational level of designing the system. Physics, Chemistry, Biology, Environmental Systems, Algebra, Geometry and of course Engineering via the design process are the most obvious. Although all of these elements may not be omnipresent throughout the process of designing, building, and testing a system, they are present in the maintenance of one. The completed project can serve as the focus of multiple classrooms that maintain it, and through it provide relevant problems for students to solve. The relevance of feeding people, too, seems like it would be engaging to a high school audience, and be situated as something that is important as a relevant issue that they can relate to.

Although the MASEE program was the impetus responsible for me completing this project, I do feel that there must be a level of understanding of what is trying to be designed before totally employing the design process independently. I did not have prior knowledge to build upon, and was too focused on figuring out what to measure rather than looking at what would work in the design itself. This obviously is because I am a novice at engineering design, as well as aquaponics and systems thinking. This lack of knowledge led me down a path that ultimately took more time than it needed. While the design process itself is a useful tool, one does gain more experience in designing, and systems thinking, by partaking in design. The mantra of situated learning, that learning comes from doing, has been exemplified in my experience with this project. I began not knowing what to measure, because engineering means quantifying to justify an approach, to learning what to measure in order to make a system more efficient and justifiable. While many researchers still trying to improve the practices of aquaponics, and their work is undoubtedly important for advancing the field, people with no prior experience must delve into designing and maintaining a system before applying their research.

I plan on continuing to try to develop interesting design projects for students in high school, with hopes to spur interest in STEM fields for their post-secondary studies. Design is a great way to grab students' attention, and keep them engaged because it gives them ownership of their work. I do believe focusing on design in high school will generate interest in Engineering. However, universities need to also reform their Engineering programs to include more design type learning to keep students interested when in minor-sequence (freshman and sophomore years). Engineering education on the K-12 level will continue to move in the direction of what was outlined by the NAE report, however, universities must also follow suit to prevent the work done by educators in high school from disappearing due to students losing interest during their early years in college.

Chapter 8

Conclusion

Engineering education in the K-12 setting should emphasize design, and do it in a fashion that allows the integration of other subjects to flow freely through the projects. This project captures the learning process of designing, building, and maintaining an aquaponics system. From it, ideas for how it could be implemented in a classroom were generated, and offered as an outline. The goal of the project was to integrate multiple subjects, in an engaging, relevant project-based setting.

Since the curriculum is an outline and many of the details have not been worked out, my next steps to develop the curriculum would be to seek out experts in developing curriculum for Biology, Chemistry, and Environmental Systems to see if they think there could be fruitful lessons developed with this project outline. There is also a need to work out the best timing for starting a project like this, and how long it could take in an engineering course. Also, what would this project look like in an Environmental Systems course? Could an Environmental Systems course include a project like this, and still learn all the TEKS required by the state, while also learning about the engineering design process? What experiments could be generated in Environmental Systems that would be fruitful for the students?

The research outlined in this report also expressed concern for actually learning the core subjects that are being integrated within the curriculum. After the development of more lessons focused on other subjects, further research could be done in order to measure the required learning of the core subjects.

While there is a need for completely fleshing out this curriculum, there is also a need for the development of problems (problem-based learning), so that other classes can help maintain these systems, while completing labs that are relevant to their core subjects. I see this particularly with regards to a Chemistry or Environmental Systems class conducting water quality testing, a Biology class learning about ecosystems, or a mathematics class that is being introduced to rates. Aquaponics systems can serve as a medium for problems and labs of these types to be experienced by students in classes that are not related to the design of the system itself.

As mentioned above the teacher taking on this research will undoubtedly have to have some experience with aquaponics or construction in order to make this project successful. However, my hope is that this curriculum would be tested in an engineering setting, where the classroom autonomy is present, while studying the interactions of other subjects and how they can enhance student learning.

Appendix

Bill of Materials for Aquaponic System	Quantity	Price Per Unit	Sub Total
Active Aqua 75 Gallon Black Reservoir	4	$116.44	$465.76
180 Gallon LDPE Reservior	1	$100.37	$100.37
110 Gallon LDPE Reservior	1	$234.58	$234.58
Mother Earth Hydroton Hydropebbles (50L)	26	$26.24	$682.24
Aquaponic Stands from Store	4	$150.00	$600.00
1" Bulkhead Slip by Thread	4	$5.94	$23.76
Botanicare Bulkhead 3/4" Tub Outlet	4	$2.12	$8.48
Botanicare Bulkhead Screen Tub Outlet	8	$0.76	$6.08
Botanicare Bulkhead 1/2" Tub Outlet	4	$2.04	$8.16
Bulkhead Riser 3/4" Slip Tub Outlet	4	$0.76	$3.04
EcoPlus 1500 Elite Submersible Pump	1	$136.57	$136.57
4" Uniseal	2	$4.55	$9.10
Schedule 40 2" x 10' PVC Solidcore Pipe	5	$7.30	$36.50
2" PVC Tee	8	$2.75	$22.00
2" PVC Cap Slip	2	$1.31	$2.62
2"Schedule 40 PVC Coupling	1	$0.89	$0.89
2" Schedule 40 PVC 45 Degree Elbow	1	$1.99	$1.99
2" x 1" PVC Schedule 40 Reducer Bushing	4	$1.86	$7.44
2" x 3/4" PVC Schedule 40 Reducer Bushing Spitgot x FIP	4	$1.99	$7.96
2" PVC Cleanout Plug	4	$0.99	$3.96
2" PVC Hub x FIPT Female Adapter	4	$1.97	$7.88
1" x 10' Schedule 40 PVC	1	$3.64	$3.64
1" Schedule 40 PVC 90 Degree Elbow	8	$0.59	$4.72
1" PVC Slip x Male Adapter	4	$2.38	$9.52
1" PVC Hub x FIPT Adapter	1	$1.24	$1.24
3/4" x 10' Schedule 40 PVC	2	$1.27	$2.54
3/4" PVC Male Adapter x Slip	4	$1.40	$5.60
3/4" PVC Female Adapter x Slip	4	$1.40	$5.60
3/4" x 3/4" PVC Slip x Slip Ball Valve	4	$7.21	$28.84
3/4" Schedule 40 PVC 90 Degree Elbow	8	$0.42	$3.36
3/4" Poly Insert Male Adapter	4	$0.43	$1.72
3/4" Poly Insert Elbows	6	$0.77	$4.62
1 1/2" x 10' Schedule 40 PVC	3	$5.26	$15.78
1 1/2" PVC Cap Slip	1	$0.87	$0.87
1 1/2" PVC Coupling Slip x Slip	4	$0.64	$2.56
1 1/2" PVC 90 Degree Elbow Slip x Slip	4	$1.31	$5.24
1 1/2" PVC Tee Slip x Slip x Slip	4	$1.80	$7.20
1 1/2" x 3/4" PVC Bushing SPG x FPT	4	$5.32	$21.28
1 1/2" PVC 45 Degree Elbow Slip x Slip	1	$1.45	$1.45
1 1/2" PVC Schedule 40 Slip x Slip Ball Valve	1	$11.85	$11.85
1 1/2" x 1" PVC Schedule 40 Reducer Bushing	1	$0.98	$0.98
3" x 10' Schedule 40 PVC	1	$14.50	$14.50
3" x 3" x 2" PVC 45 Degree Hub x Hub x Hub Wye	1	$4.28	$4.28
3" x 2" PVC Reducer Bushing	1	$2.39	$2.39
3" PVC 90 Degree Hub x Hub Elbow	1	$2.39	$2.39
4" x 10' PVC Schedule 40 Plain End Pipe	1	$19.33	$19.33
4" x 4" x 4" PVC Hub x Hub x Hub Sanitary Tee	1	$13.84	$13.84
Stainless Steel Clamps (10)	2	$7.86	$15.72
Bag of Sand (48 lb)	4	$3.77	15.08
Concrete Blocks 4" x 8" x 16"	16	$1.16	$18.56
3/4" x 18" PVC Threaded Riser	4	$1.55	$6.20
Oatley 32 oz. PVC Purple Primer	1	16.27	16.27
Oatley 32 oz. Clear Medium Body Cement	1	13.07	13.07
TOTAL:	$2,580.44		

Table 3: Bill of Materials for Buono Design

ITEM	#	Price	Total	URL
API Freshwater Master Test Kit	2	$28.99	$57.98	http://www.amazon.com/API-Freshwater-Master-Test-Kit/dp/B000255NCI
Hanna Instruments HI98127 pH/Temp Test Kit	2	$89.00	$178.00	http://www.amazon.com/Hanna-98127B-Home-Beer-Temp/dp/B003IKNJP2/ref=sr_1_1?ie=UTF8&s=industrial&qid=1287414715&sr=1-1
AquaUp For Raising pH - 10lb	1	$39.95	$39.95	http://www.theaquaponicstore.com/AquaUp-pH-Raising-Kit-10lb-p/awcas0037.htm
Hydro-Logic 36005 Small Boy with upgraded KDF85/Catalytic Carbon Filter	1	$129.45	$129.45	http://www.amazon.com/Hydro-Logic-36005-upgraded-Catalytic-Carbon/dp/B008KL0JG6/ref=sr_1_1?ie=UTF8&qid=1405440772&sr=8-1&keywords=small+boy+filter
Dura-Skrim Liner - 6' x 100'	1	$304.95	$304.95	http://www.theaquaponicstore.com/Dura-Skrim-Liner-6-x-100-p/cwhga015.htm
Raven Butyl Seal 2-Sided tape (2" x 50')	2	$34.95	$69.90	http://www.theaquaponicstore.com/Dura-Skrim-Sealing-Tape-s/215.htm
Vaporbond 4" Tape TBV4 (4" x 210')	1	$49.95	$49.95	http://www.theaquaponicstore.com/Dura-Skrim-Sealing-Tape-s/215.htm
Safety Glasses	15	$2.08	$31.20	http://www.grainger.com/product/5JDW7?gclid=CLnag4jRxb8CFUwV7AodDlAAQw&cm_mmc=PPC:GooglePLA-_-Safety-_-Eye%20Protection%20and%20Accessories-_-5JDW7&ci_src=17588969&ci_sku=5JDW7&ef_id=UzhUUAAABY4K1rhH:20140714202339:s
Aquaponic Gardening: A Step By Step Guide to Raising Vegetables and Fish Together	15	$29.99	$449.85	http://www.amazon.com/s/ref=nb_sb_noss_1?url=search-alias%3Daps&field-keywords=aquaponic%20gardening&sprefix=aquaponic+ga%2Caps
Ice Hardened Bi-Metal Hole Saw kit (13-Piece)	1	$79.97	$79.97	http://www.homedepot.com/p/Milwaukee-Ice-Hardened-Bi-Metal-Hole-Saw-Kit-13-Piece-49-22-4025/202327772?N=5yc1vZc268
M12 12-Volt Lithium-Ion 3/8 in. Cordless Drill/Driver Kit	1	$99.00	$99.00	http://www.homedepot.com/p/Milwaukee-M12-12-Volt-Lithium-Ion-3-8-in-Cordless-Drill-Driver-Kit-2407-22/204300706?N=5yc1vZc27fZ1z140i3
Ryobi 14-Amp 10 in. Compound Miter Saw	1	$119.00	$119.00	http://www.homedepot.com/p/Ryobi-14-Amp-10-in-Compound-Miter-Saw-TS1344L/100634340
10 in. x 5/8 in 60T Micro-Polished Miter Saw Blade	1	$37.00	$37.00	http://www.homedepot.com/p/Makita-10-in-x-5-8-in-60T-Micro-Polished-Miter-Saw-Blade-A-93675/203298122
Milwalkee 12-AMP Sawzall	1	$69.99	$69.99	http://www.cpomilwaukee.com/factory-reconditioned-milwaukee-6519-830-12-amp-sawzall-reciprocating-saw-with-1-1-8-in--stroke/milr6519-830,default,pd.html?ref=milwaukeecipla&zmam=31282435&zmas=47&zmac=665&zmap=milr6519-830&srccode=cii_17588969&cpncode=34-
Milwalkee Sawzall Blade Set	1	$24.97	$24.97	http://www.homedepot.com/p/Milwaukee-Sawzall-Blade-Set-12-Piece-49-22-1135/203820340?N=5yc1vZc2jg
GRAND TOTAL		$1,741.16		

Table 4: Sample List of Materials Needed for Classroom Project

Aquaponic Food System Design Brief

Client: Small Family Living in Texas

Target Consumer: Adults and/or small families

Designers: ______________________________

Problem Statement: Environmental degradation and rising food prices can result from modern agribusiness practices and scarce resources. Design, build, test, maintain and troubleshoot a backyard aquaponic system in order to grow food more sustainably, and sell the food for a profit or supplement grocery bills.

Design Statement: Design, build, test and optimize an inexpensive, reliable, aquaponic system that a small family can use to supplement their grocery bill and or sell fresh produce.

Constraints and Requirements:

1. All parts must be under $300.
2. Must document the engineering design process throughout.
3. Must calculate the cost to design, build, and operate the system.
4. Must calculate the time required in order for the system to pay for itself (or turn a profit). This includes finding the feed conversion ratio of the fish, power cost, stocking densities, and plant economics.
5. Must use 120V household power for the pump
6. Must be an outdoor media based aquaponic system
7. Must prove the system is structurally sound by finding the factor of safety

KNOWS	NEED TO KNOWS
(What does the entry document tell you about the project?)	*(What information do you still need to figure out in order to complete the project?)*
1.	*1.*

Research Information Aide: What are the 3 parts of the aquaponic cycle?

Aquaponic Cycle Component	Relation to Nitrogen Cycle *How does this happen? What factors are involved?*	What part of a media based system houses this component?

Types of Systems

Type of System	Main Characteristics of System	Benefits	Limitations

Types of Systems

Type of System	Main Characteristics of System	Benefits	Limitations

Existing System Research

Group Members: ____ Date:_____________

System Type: ______________________ System Location: _____________________

System Description and Background Information	Diagram / Picture of System

Performance Metrics - Systems should have basic information listed below. These are a good start as to some of the things we will be measuring in our systems. For now, try to find systems that have information like this, so we can compare data to other groups.

Metric		Did they have a justification in their design? If they did, explain.
Pump Capacity		
Fish Tank Size		
Grow Bed Area		
Fish Tank to Grow Bed Ratio		

Estimated LBS of Fish per year: _________

Estimated LBS of Vegetables per year: ___________

Reflection *(What do you think of the design? Does it have any limitations we should know about?):*

____
____
____
____
____
____
____
____

Works Cited

"2013 World Population Data Sheet." . Population Reference Bureau, n.d. Web. 2 Jul. 2014. <http://www.prb.org/pdf13/2013-population-data-sheet_eng.pdf>.

Affnan. "Affnan's Aquaponics." *Affnan's Aquaponics*. N.p., n.d. Web. 15 July 2014. <http://www.affnanaquaponics.com/>.

"Aquaponics System." *Aquaponics System RSS*. N.p., n.d. Web. 1 Aug. 2014. <http://aquaponics-system.com//wp-content/uploads/bell-siphon.jpg.png)>.

"Backyard Aquaponics: A Place to Discuss Aquaponics." *Backyard Aquaponics • Index Page*. N.p., n.d. Web. 12 July 2014. <http://www.backyardaquaponics.com/forum/>.

Berland, Leema. "Designing for STEM Education." *Journal of Pre-College Engineering Education Research* 3: 22-31. Web. 1 Jan. 2014.

Bernstein, Sylvia. *Aquaponic Gardening A STEP-BY-STEP GUIDE to RAISING VEGETABLES and FISH TOGETHER*. Gabriola Island, BC, Canada: New Society Publishers, 2011. Print.

Connally, Keith, and Tatjana Trebic. (2010). Optimization of a Backyard Aquaponic Food Production System. McGill University. Web. 2 March 2014. < http://backyardaquaponics.com/Travis/Aquaponics-Design.pdf>.

"Discussion Forum." - *Aquaponic Gardening*. N.p., n.d. Web. 12 July 2014. <http://community.theaquaponicsource.com/forum>.

Doll, William E. *A Post-modern Perspective on Curriculum*. New York: Teachers College, 1993. Print.

"Dried Out: Confronting The Texas Drought." *Texas drought maps and photos*. National Public Radio, 1 Jan. 2011. Web. 2 July 2014. <https://stateimpact.npr.org/texas/drought/>.

Endut, A., Jusoh, A., Ali, N., Wan-Nik, W., & Hassan, A. (2010). A Study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic system. *Bioresource Technology* , 1511-1517.

Hallam, Murray. "Murray Hallam's Practical Aquaponics." *Murray Hallams Practical Aquaponics*. N.p., n.d. Web. 12 July 2014. <http://practicalaquaponics.com/blog/>.

National Academy of Engineering, and National Research Council. *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*. Ed. Linda Katehi, Greg Pearson, and Michael A. Feder. Washington, D.C.: National Academies, 2009. Print.

Kubel, Ed. "Keeping the STEM pipeline full." *Advanced Materials & Processes* 170.4 (2012): 2. *Academic OneFile*. Web. 2 Mar. 2014.

"Manage the nitrogen cycle - Engineering Challenges." *Manage the nitrogen cycle - Engineering Challenges*. National Academy of Sciences, 1 Jan. 2012. Web. 2 July 2014. <http://www.engineeringchallenges.org/cms/8996/9132.aspx>.

Modak, Jayant M.. "Haber process for ammonia synthesis." *Resonance* 7: 69-77. Print.

Singer, Susan Rundell. "STEM education: time for integration." *Peer Review* 13.3 (2011): 4+. *Academic OneFile*. Web. 2 Mar. 2014.

Wardlow, George W., Donald M. Johnson, Carol L. Mueller, and C. Eugene Hilgenberg. "Enhancing Student Interest in the Agricultural Sciences through Aquaponics." *Journal of Natural Resources and Life Sciences Education* 31 (2002): 55-58. *JNRLSE*. Web. 10 July 2014.

"WWF 2008 Living Planet Report." *WWF*. World Wildlife Foundation, n.d. Web. 2 July 2014. < http://d2ouvy59p0dg6k.cloudfront.net/downloads/living_planet_report_2008.pdf>